Volume XLIII August 1948 Number 5

Economic Geology

and the

Bulletin of the Society of Economic Geologists

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PUBLISHED SEMI-QUARTERLY

Five Dollars a Year, One Dollar a Copy

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Printed by Lancaster Press, Inc., Prince and Lemon Streets, Lancaster, Pa.

Entered as second-class matter, March 30, 1906, at the Post Office at Lancaster, Pa., under the Act of Congress of March 3, 1879

Economic Geology

and the

Bulletin of the Society of Economic Geologists

Issued Semi-Quarterly and sent to subscribers on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15.

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Indexed in the Industrial Art Series.

LANCASTER PRESS, INC., LANCASTER, PA.

ECONOMIC GEOLOGY

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VOL. XLIII AUGUST, 1948 No. 5

TIN-SILVER VEINS OF ORURO, BOLIVIA.*

F. M. CHACE.

PART I.

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ABSTRACT.

The tin-silver ores of Oruro, Bolivia, occur in complex veins that are found in and adjacent to small stocks of quartz latite porphyry. The stocks have volcanic affinities and evidently were intruded at a relatively shallow depth into folded Paleozoic sedimentary rocks, chiefly argillite, and were accompanied or followed by extrusive lava flows. The San José breccia, of explosive origin, occurs as pipes, dikes and irregular bodies in the vicinity of the mineral deposits.

* Published with the permission of Compañia Minera de Oruro. Abstract of a Ph.D. Dissertation, Harvard University.

The hypogene mineralization followed a system of pre-mineral fractures, which are a combination of shear and tension breaks that occur in four clusters: the San José-Socavón, the Itos, La Colorada, and Tetilla. During ore deposition telescoping took place, with reopening of vein fractures and superimposition of silver- and tin-bearing lead sulpho-salts and sulpho-stannates on a relatively simple early mineralization of quartz, pyrite, and cassiterite. The fractures were caused by differential vertical stresses set up in local areas following igneous intrusion and formation of the San José breccia. Fracturing was closely related to the process of mineralization, both in time and place, and possibly in cause.

The mineralogy suggests that deposition took place during a wide range of temperature conditions, and it is inferred that ore deposition occurred at relatively shallow depths. The deposits may be classed as xenothermal.

Erosion and deep oxidation developed a gradational capping of oxidized or "pacos" ores, composed of cassiterite, limonite, jarosite, and quartz, at the outcrops of the primary sulphide veins. Tin is still mined from the oxidized zone, but the bonanza silver ores were mined out many years ago.

PART I.

INTRODUCTION.

THE Oruro mining district of Bolivia is an important member of the tin-silver metallogenetic province in the Eastern Cordillera of the Andes Mountains, which extends from Lake Titicaca on the north to the Argentine border on the south and includes the famous mining districts of Llallagua and Potosí. Silver is reported to have been obtained from Oruro prior to the discovery of the district by the Spaniards in 1595, sixty-two years after the conquest of the Incas by Pizarro, and fifty-one years after the bonanza of Potosí, 250 kilometers to the south, had been found in 1544. Mining of tin, however, did not begin at Oruro until late in the nineteenth century.

The silver bonanzas of the province, particularly Potosí and Oruro, supplied a large amount of the precious metal obtained by the Spanish adventurers in their looting of the Latin American countries. Potosí, long famous as the greatest silver camp in the world, is estimated to have yielded over two billion ounces since the time of its discovery.[1] Oruro, while less spectacular, has been the source of more than 271,000,000 ounces; although only 36 percent of Potosí's total output, this places Oruro in the ranks of the major silver-mining districts of the world. By way of comparison, Leadville, Colorado, one of the United States' leading silver-producing districts, is estimated to have produced a total of 232,529,400 ounces in the period from 1859 to 1926.[2]

It is interesting to note that although the desire for precious metals was the incentive for exploration in this difficult region, and fabulous quantities of silver rewarded the Spanish Conquistadores, the production of this metal has gradually given way to that of tin. Although Bolivia still accounts for about

[1] Evans, David L., Structure and mineral zoning of the Pailaviri Section, Potosí, Bolivia: ECON. GEOL., vol. 35, pp. 737–750, 1940.

[2] Henderson, C. W., Geology and ore deposits of the Leadville mining district, Colorado: U. S. Geol. Survey Prof. Paper 148, chapter 7, 1927.

15 percent of the world's annual silver output, it is now noted principally as one of the leading tin-producing countries of the world. No doubt the presence of tin was known to the Spaniards,[3] but it was not until the latter part of the nineteenth century that this metal became an important product. At first, tin was recovered from deposits where the ores of silver were mixed with cassiterite, as, for example, at Oruro and Potosí, but gradually other deposits containing tin alone were found and exploited; among these the rich veins at Llallagua are the outstanding examples. A few districts, including Oruro, still win substantial profit from both metals. However, in surprising contrast to the early days of the camp, the supply of silver ore appears to be exhausted at Potosí, and tin alone maintains the life of this famous old mining camp.

Location.—The mining district of Oruro is located in an isolated group of hills known as the "Cerros de Oruro" which rise above the high plateau or altiplano of central Bolivia at approximately 17° 58′ south latitude and 67° 04′ west longitude. Oruro is about 200 km (124 miles) southeast of La Paz, the nominal capital of Bolivia, and is about 345 km (214 miles) inland from the Pacific Ocean and Chilean coast (Fig. 1). The city of Oruro is on the altiplano at an elevation of approximately 3,720 meters (12,200 feet) in an embayment in the "Cerros de Oruro" about 8 km (5 miles) west of the Cordillera Real, the eastern range of the Bolivian Andes.

Oruro is the center of the railroad and mining activities of central Bolivia and in 1936 had a population estimated at 44,800. The city is on the main line of the "Antofagasta (Chile) and Bolivia Railway Co.," which runs from La Paz to Antofagasta on the Chilean coast, and connects with lines which run to Buenos Aires, far to the southeast on the Atlantic seaboard in Argentina. Arica, on the coast of northern Chile, is also connected by railroad via La Paz; and Mollendo, a seaport town in southern Peru, may be reached by crossing Lake Titicaca by boat and then going by railroad to the seacoast. Spur railway lines connect Oruro with Cochabamba, Llallagua and Potosí. Panagra Airlines, a subsidiary of Pan American Airways and Grace and Co., maintains a regular schedule through central Bolivia.

Scope of Investigation.—This report, based on six months' field work in Bolivia during 1937 and subsequent research at Harvard University on the ores and rocks, is primarily concerned with the tin-silver veins of Oruro, including their structure, mineralogy, and origin. The general geology of the Oruro district was studied in much less detail, but sufficiently, it is believed, for an adequate understanding of the geologic environment of ore deposition. Although considerable progress was made in an understanding of the ore deposit and its geologic environment, many unsolved problems remain. These will be pointed out in the text.

Previous Geologic Work.—Although the Oruro district has been known for over 300 years, and the bibliography on the area is rather long, most of the investigators have confined themselves to individual aspects of the mineralogy or have dealt in generalities without giving a clear picture of the area. Prior to 1938, no one had adequately described the geology, vein structure, and

[3] Rickard, T. A., Man and Metals, vol. II, pp. 685–709, New York, 1932.

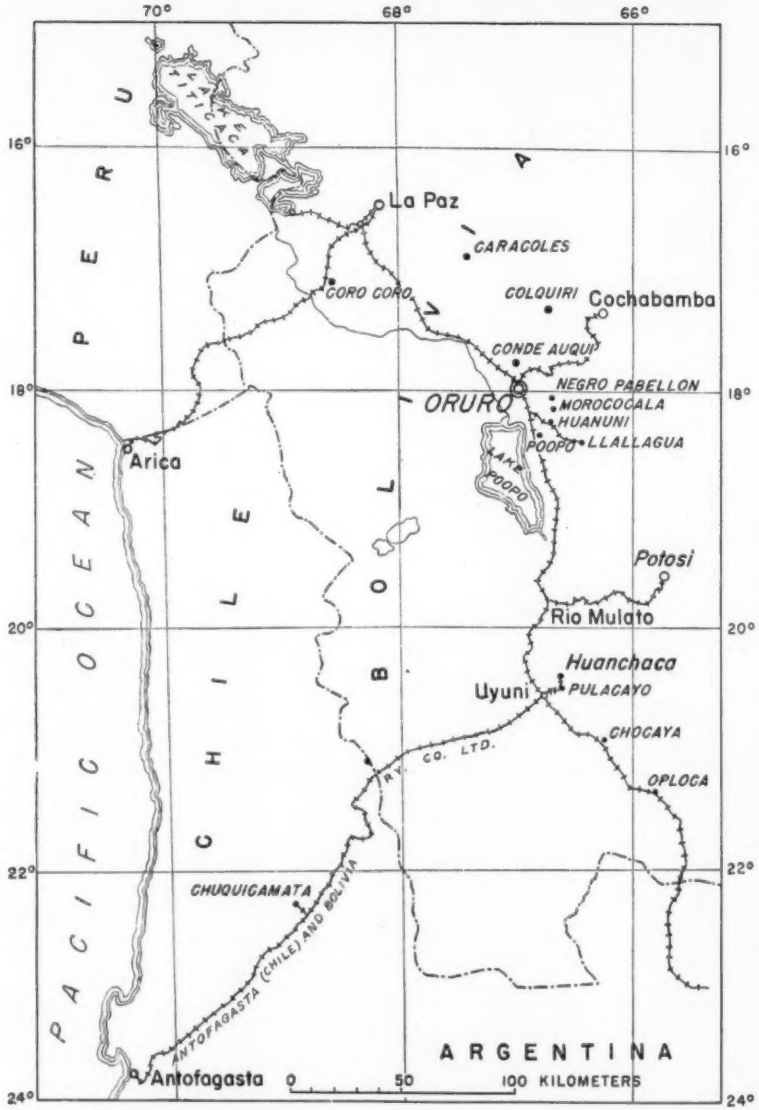

FIG. 1. Map showing the position of Oruro, Potosí, Llallagua and other mining districts of the Bolivian tin-silver metallogenetic province.

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mineralogy in sufficient detail to give a comprehensive understanding of the ore deposits.

In 1931 a paper of considerable value was published by Lindgren and Abbott.[4] This was based on a few days' visit to Oruro by the senior author in 1921 and a laboratory study of a suite of specimens at the Massachusetts Institute of Technology. Although the paper is remarkably good for such a brief survey, it is far from complete. The mineralogy of the veins is treated in detail, but as it was based on a collection that was too limited to be representative of the district, the resulting general picture is somewhat misleading.

Kozlowski and Jaskolski, former teachers at the Oruro School of Mines, published in 1932 the most complete description and discussion up to that time.[5] Their paper contains a description of the general geology and mineralogy, but gives little attention to vein structure. Numerous references are made to the work of these men in the following pages, and, while general agreement is reached on numerous points, considerable difference arises in interpretation and conclusions.

Following the author's work on Oruro in 1937 and 1938, a geologic staff was established at Oruro by Compañia Minera de Oruro. H. G. Leggett served as Chief Geologist and was assisted by Donald F. Campbell. Their work culminated in 1942 in a publication in Economic Geology by Campbell,[6] who spent considerable time mapping the surface and upper mine workings. Campbell arrived at an interpretation of the district geology quite different from that of previous workers. This will be discussed in the following text.

Acknowledgments.—The author is greatly indebted to Dr. Donald H. McLaughlin, former professor of mining geology at Harvard University, under whom the original manuscript was prepared, and to Professor L. C. Graton, of Harvard University, for their constant advice and guidance. Grateful acknowledgment is also made to Professor Russell Gibson of Harvard University, who spent a few days in the field with the author. Professor F. S. Turneaure, of the University of Michigan, read the manuscript and made many useful suggestions.

The late William Val de Camp, former general manager of the Mauricio Hochschild mining properties in Bolivia, made the study possible and, together with H. J. de Wijs, of Compañia Minera de Oruro, gave valuable cooperation and assistance during the mine examination at Oruro.

TOPOGRAPHY.

The Andes Mountains are the principal topographic feature of Bolivia, with a high plateau, known as the altiplano, lying between two well-defined ranges. The Andes follow a northerly trend from Cape Horn to the southern border of Bolivia, where they divide into two mountain chains, the Cordillera

[4] Lindgren W., and Abbott, A. C., The silver-tin deposits of Oruro, Bolivia: ECON. GEOL., vol. 26, no. 5, pp. 453–479, 1931.

[5] Kozlowski, R., and Jaskolski, S., Les gisements argento-stannifères d'Oruro en Bolivie: Archive de Minéralogie de la Société des Sciences de Varsovie, 8, pp. 1–100, 1932.

[6] Campbell, Donald F., The Oruro silver-tin district, Bolivia: ECON. GEOL., vol. 37, pp. 87–115, 1942.

Real and the Cordillera Occidental, separated by the altiplano. At latitude 18° south, near Oruro, the ranges swing abruptly to the northwest and cross the northern border of the country at Lake Titicaca.

The altiplano is an extensive, level plain from 12,000 to 13,000 feet above sea level. Throughout most of its extent, the eastern margin is well defined by the sharp rise and straight front of the Cordillera Real. Irregular hills of volcanic débris along the Cordillera Occidental mark the less uniform western limit of the high plateau. The broad, flat expanse of the altiplano is marked by isolated low ridges and groups of subdued hills, generally elongated north-south, parallel to the main ranges of the Cordillera. At the present time, the plateau is a basin of accumulating sediments. Many of the hills appear to be partially buried in their own débris.

Topographically, the region reminds one forcibly of the Basin and Range province of Utah and Nevada. There is ample evidence that in the past large areas of the altiplano were covered by a great lake; vestiges of an inland body of water are found, but conspicuous beach lines, such as those which mark the limit of glacial Lake Bonneville, are lacking. However, in places, remnants of old strand lines are found on the hill slopes.

The altiplano is a typical interior basin, characterized by inland drainage. However, in comparatively recent time the La Paz river has cut through the Cordillera Real, and now a part of the basin drains into the Amazon Valley. On the altiplano is an extensive, deep, fresh-water body, Lake Titicaca, and an important river, the Desaguadero.

The "Cerros de Oruro," in which the tin-silver ore deposits are located, occupy an oval-shaped area six kilometers along its northerly axis and one to three kilometers wide. The hills are completely surrounded by the nearly featureless altiplano, or "pampa," as it is referred to locally, which in the vicinity of Oruro has an altitude of 3,700 meters. Figure 6 is a generalized contour map of the Oruro hills and environs, showing the nature of the topography, the position of the city, and the location of the various mines.

The "Cerros de Oruro" rise 100 to 300 m above the altiplano, and two of the peaks reach an elevation of over 4,000 m above sea level. San Felipe Mountain, the highest of the group, has an altitude of 4,030 m, and San Pedro Mountain, an altitude of 4,010 m. The slopes of the hills are generally smooth, devoid of vegetation with the exception of scattered cactus and coarse pampa grass, and the summits are easily accessible. The crests of the hills are smooth and have been swept clean of talus, leaving large areas of exposed bed rock or only a thin veneer of gravel.

The inclination of the hill slopes averages about 20°. At their lower limit a break in slope marks the line where bed rock gives way to unconsolidated sediments of the altiplano, which grades off toward the intermontane area at about 10°.

In the vicinity of Oruro, the altiplano is a gently undulating plain with many broad, flat areas. The surface is composed of a compact, fine-textured mud, yellow to white in color, which reflects the rays of the bright, tropical sun in a dazzling manner. Patches of gravel and sand near the foothills give way to playas and salt pans in the lower parts of the basin. During the rainy

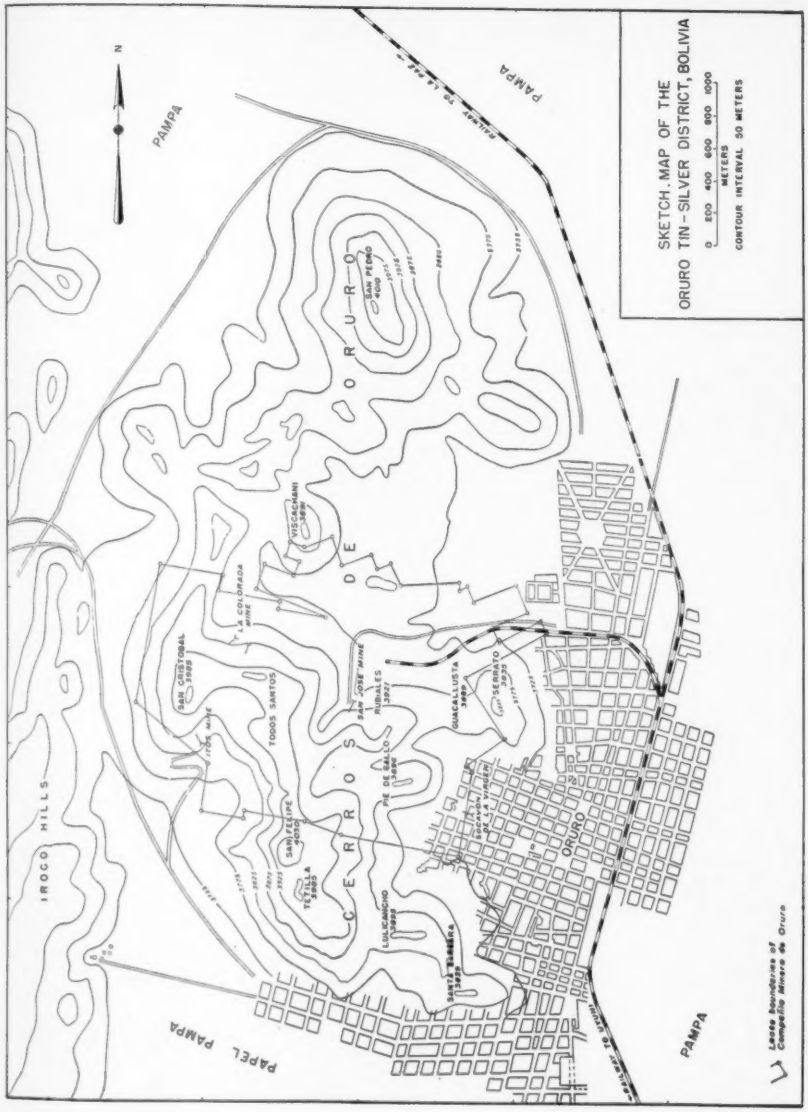

FIG. 6. A generalized contour map of the "Cerros de Oruro" and environs, showing the topography, and the location of the city, the mines, and the Iroco Hills to the west.

season, large areas are inundated, but as the dry season progresses, the water evaporates, leaving a mud-cracked surface and extensive "salars." The pampa is generally devoid of vegetation with only scattered patches of coarse pampa grass, yareta, and tola bushes.

In several localities in the neighborhood of Oruro, sand dunes are migrating across the pampa. They are usually irregular in outline, but occasionally barchans are found.

Drainage.—The Desaguadero River is the principal drainage channel of the altiplano. It flows out of Lake Titicaca, winds across the pampa 15 km west of Oruro, and empties into Lake Poopó, a large salt-water body 20 km south of the city. Lake Poopó has no outlet, but during the rainy season it overflows into an extensive swamp.

In the vicinity of Oruro there are no permanent streams, and run-off is in the nature of sheet wash. At the foot of the "Cerros de Oruro" numerous gullies have cut into the pampa. They form a dendritic pattern with broad, flat surfaces between them. Toward the center of the altiplano the gullies become distributary, and deposition rather than erosion takes place. Placer tin is found in the channels, but the gravels have never been systematically sampled.

GENERAL GEOLOGY.

The bedrock of the Oruro mining district is made up of a group of closely spaced, quartz latite porphyry plutons of Pliocene (?) age intrusive into folded Paleozoic sedimentary rocks. The Paleozoic rocks, chiefly argillite, shale and slate, are here named the Oruro formation. Quartz latite and dacite lava flows are present locally; the former may grade into intrusive quartz latite porphyry and may have formed contemporaneously with one of the plutons. An explosion breccia, referred to in the present paper as the San José breccia, occurs in the vicinity of the mines, follows contacts between porphyry and the Oruro formation, and cuts both of these rock bodies in pipes, dikes and irregular bodies.

The summits and slopes of the Cerros de Oruro are underlain by fairly fresh, resistant quartz latite porphyry and in several places the individual knobs are separate plutons, probably small stocks. The lower slopes and valleys are underlain by less resistant, folded argillite and shale, and locally by highly altered igneous rocks. The larger valleys were probably localized by areas of easily eroded Oruro formation, and the entire group of hills is outlined roughly by shale or argillite. These observations suggest that the relief of the Cerros de Oruro was caused by differential erosion and not by structural movements.

An extensive mantle of unconsolidated gravel, sand, and clay known as the "Pampa Formation" rests on the eroded surface of the Oruro formation, completely surrounds the hills, and extends across the altiplano in all directions.

In terms of rock types, the geology of Oruro is rather simple and the column incomplete, but from the structural point of view, the geology is complex. An outline of the rock formations of the Oruro district is given in the accompanying table (Fig. 7).

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ORURO MINING DISTRICT — BOLIVIA

ERA	PERIOD	EPOCH	FORMATION
CENOZOIC	QUATERNARY	Recent	Sand dunes, salars Stream deposits Alluvial deposits silt, sand, gravel
		Pleistocene	Pampa Formation lake beds, sand, silt
	TERTIARY	Pliocene (?)	San José explosion breccia pipes, dikes, irregular bodies Lava flows quartz latite porphyry rhyolite (?) dacite Intrusions quartz latite porphyry plutons stocks, dikes, sills
PALEOZOIC	DEVONIAN (?)		Oruro Formation argillite, shale, slate quartzite, (no fossils)

FIG. 7. Table of rock formations.

The Sedimentary Rocks.

The Oruro Formation.—The oldest rocks exposed in the district are a series of folded Paleozoic sedimentary rocks variously referred to by different authors as shale, slate, or argillite. All three types occur, and the name which is applied varies with the degree to which the rock has been metamorphosed. It is difficult to decide which type is most widespread. As all varieties were originally argillaceous and have been somewhat recrystallized without the development of secondary cleavage, except locally, probably the term argillite would be more applicable than shale or slate to the group as a whole. However, to avoid difficulties of terminology, and because the sedimentary rocks are sufficiently widespread to justify it, the name Oruro formation is here given to this group of rocks.

The argillaceous rocks are dark gray to black in color where fresh, but on the surface, weathering has bleached them to brown and bluish gray and has accentuated the bedding planes. The Oruro formation appears more shaly on the surface, where disintegration and decomposition have affected it,

than on the deeper mine levels. Thin, sandy layers, locally quartzitic, are common in the mine. In places the formation is hard and massive without traces of bedding; elsewhere, secondary cleavage is developed, and in a few localities the rock is schistose. Near the intrusive igneous rocks on the deeper mine levels, the formation is hard and silicified, and in a few places a spotted slate or "knotenschiefer" has resulted from contact metamorphism. The spots appear to have been caused by a concentration of carbonaceous matter in small circular areas, 1 to 3 mm in diameter.

Under the microscope, the fresh argillaceous rock is seen to be composed of angular to poorly rounded quartz grains with a few rounded zircon crystals scattered through a matrix of sericite and chlorite. A small amount of carbonaceous matter provides the dark pigmentation. It is apparent that a certain amount of recrystallization has taken place in most of the sedimentary rock.

The Oruro formation is well exposed on the lower hill slopes, in the radiating gullies, and on the lower mine levels. The actual areal extent on the surface in the vicinity of the mines is small, but the amount increases rapidly in depth, and the bottom levels of the mine are nearly all in argillite or slate. The reason for this distribution will become apparent when the form of the igneous rock bodies is described.

Isolated areas of the Oruro formation occur between intrusive bodies—sometimes in long narrow septa. The most conspicuous septum occurs on the south slope of San Pedro Mountain and can be traced for about one kilometer. It varies from 1 to 20 m in width and strikes N 30° W. Porphyry adjoins the formation on both sides with a sharp contact. Similar septa occur throughout the district, although they are less extensive than the one at the foot of San Pedro Mountain.

The Oruro formation has been highly folded, and steep dips are the rule. In places, the intensity of the deformation increases with proximity to the intrusive igneous bodies. In the "Cerros de Oruro" the beds are not consistent in attitude even for a short distance. In the Iroco Hills, to the west of Oruro, sedimentary rocks are well exposed with a prominent quartzite member. Here the strike is uniformly north parallel to the elongation of the hills, and the dip varies from 65° to 75° west. These beds appear to form the west limb of a major anticline. By projection, if the fold is symmetrical, the east limb should appear on the east side of the Oruro hills, but as the later Pampa formation covers the entire area, the rocks are not exposed.

This interpretation has been questioned by Campbell,[7] who states that the Iroco Hills consist of a faulted anticline overturned to the east. However, no supporting evidence is given for this statement. Features indicative of overturning were not observed by the author.

The sedimentary rocks have not been subdivided stratigraphically because of their limited extent in the "Cerros de Oruro" and because of the lack of a good horizon marker. As they contain no fossils, their age is uncertain.

[7] Campbell, Donald F., The Oruro silver-tin district, Bolivia: Econ. Geol., vol. 37, p. 99, 1942.

According to Lindgren,[8] the nearest fossils are found in the vicinity of Viacha, 200 km (124 miles) to the north. Here the rocks are considered to be Silurian or Devonian. The Oruro rocks resemble those of the Viacha area, and by analogy are believed to be of the same age. Moreover, the Oruro sediments are lithologically similar to the highly folded rocks of the nearby eastern Andes which are believed to belong in the lower middle part of the Paleozoic section. At Llallagua, 75 km (47 miles) southeastward, similar rocks are considered to be Devonian.

The Pampa Formation.—In the vicinity of Oruro the altiplano is underlain by an extensive mantle of unconsolidated sediments known as the "Pampa Formation." It is made up of gravels, sands, and clays of terrestrial origin derived by erosion from the Paleozoic sedimentary rocks and the quartz latite porphyry outcrops of the hills. These sediments are usually well sorted, and bedding is prominent. In a few places, cross bedding is well exposed. Where recent gullying has cut through the formation to bedrock at the foot of the "Cerros de Oruro" it has a maximum thickness of about 10 m. The thickness, however, increases appreciably toward the center of the pampa.

The deposits of the "Pampa Formation" are widespread in central Bolivia, underlying the altiplano throughout most of its extent. According to Kozlowski and Jaskolski,[9] the sand and gravels around the Oruro Hills change laterally to a yellowish-brown, lacustrine clay toward the center of the basin. In places the formation is impregnated with calcite or is associated with calcareous tufa as much as 1 m thick and locally contains gastropod shells of living species. The deposits, therefore, are believed to have been laid down in a lake that surrounded the Oruro Hills and covered much of the province now known as the altiplano. In the vicinity of La Paz, where erosion has cut deeply, the Formation has great thickness.

These deposits were probably formed during the pluvial cycle that accompanied Pleistocene glaciation. During this period, the surface of the hills, such as the "Cerros de Oruro" were washed clean of their talus, and the débris was deposited in the intermontane basin, now underlying the altiplano.

Ancient Shore Lines.—In a few places, on the slopes of the hills, a crust of travertine has been found and interpreted as an old strand line. Kozlowski and Jaskolski[10] report that this travertine contains shells of gastropods of warm, terrestrial water, belonging to species living today in the interior basins. They state that at the time of the deposition of the travertine, the level of the surface of the inland lake stood 40 m above the present surface of the pampa in the vicinity of Oruro. Above this line of travertine, on the south slope of Santa Barbara and on the hills south of Iroco, the remains of another terrace of travertine, 20 m above the first, marks a level of the lake more ancient than the first.

Recent Sediments.—Alluvial fans, talus cones, and wind-blown sand make up the recent sediments. The alluvial deposits contain placer tin, but their

[8] Lindgren, W., and Abbott, A. C., The silver-tin deposits of Oruro, Bolivia: ECON. GEOL., vol. 26, pp. 453–479, 1931.
[9] Op. cit.
[10] Op. cit.

extent has not been investigated. Sand dunes, some of which have a perfect crescent or barchan form, are present in several areas.

The Igneous Rocks.

Intrusive and extrusive porphyritic igneous rocks make up the greater part of the Cerros de Oruro and have a greater areal extent than all the other rocks of the district. They form an oval unit, elongated north-south parallel to the regional, geographical trend of the hills and mountain ranges of central Bolivia, and in part were intruded along steeply dipping Paleozoic sediments with a pronounced north-south strike which undoubtedly influenced the elongated form of the Oruro Hills. The prevailing rock type is an altered quartz latite porphyry which forms small stocks, sills, dikes, irregular bodies, and lava flows.

Although various geologists have considered that the igneous rocks of the Oruro Hills were components of one irregular intrusion with roof pendants of sedimentary rocks, considerable evidence has accumulated which indicates that there are several centers of intrusion in the "Cerros," and that in certain cases separate hills or groups of hills are individual stocks. Within the mineralized area two separate intrusions occur—the Itos or San Cristobal stock and the San José stock. The latter stock outcrops in a large, irregular area on Rubiales, Pie de Gallo, and Todos Santos Hills, but in depth, narrows to elongated, dikelike bodies. Other hills, such as San Pedro, Viscachani, and San Felipe, are probably individual stocks separated from other igneous bodies by argillite beds or long, narrow septa of the Oruro formation such as that exposed on the northeast slope of San Pedro Hill (Figs. 4, 5).

San Pedro Hill is the largest intrusive mass in the district, with an outcrop over 2 m long and 1.8 km wide, and, where exposed, is separated from other intrusives by argillite and volcanic rocks. Elsewhere its contacts are too obscured by talus to determine the relationship, but probably San Pedro is an individual intrusive center. The size and shape of these detached bodies at depth, and the attitude of their contacts, are not known, for there are no mine workings in them.

San José Stock.—The San José stock is the best known of all the rock bodies in the Oruro district because of the extensive mine workings that penetrate it. Its outcrop is extremely irregular in outline and covers a roughly elliptical area including Pie de Gallo, Rubiales, La Colorada, Todos Santos, and Guackallusta Hills; and, since the same rock type extends beyond Cerro de San Felipe to the south, it may also include this hill. The long axis of the body strikes roughly N 45° W and is 1.7 km long; the short axis is over 1 kilometer long (Figs. 8, 9 and 10).

The horizontal cross section of the San José stock exposed on the lower mine levels is much smaller than on the surface. On the –200 level of the San José mine, the igneous rocks form dikelike bodies separated by septa of Oruro formation (Figs. 8, 11). Here about 50 percent of the exposed rock is porphyry; the other 50 percent is Oruro formation. The principal dike on this level trends N 50° W, has a maximum width of 130 m, and is at least

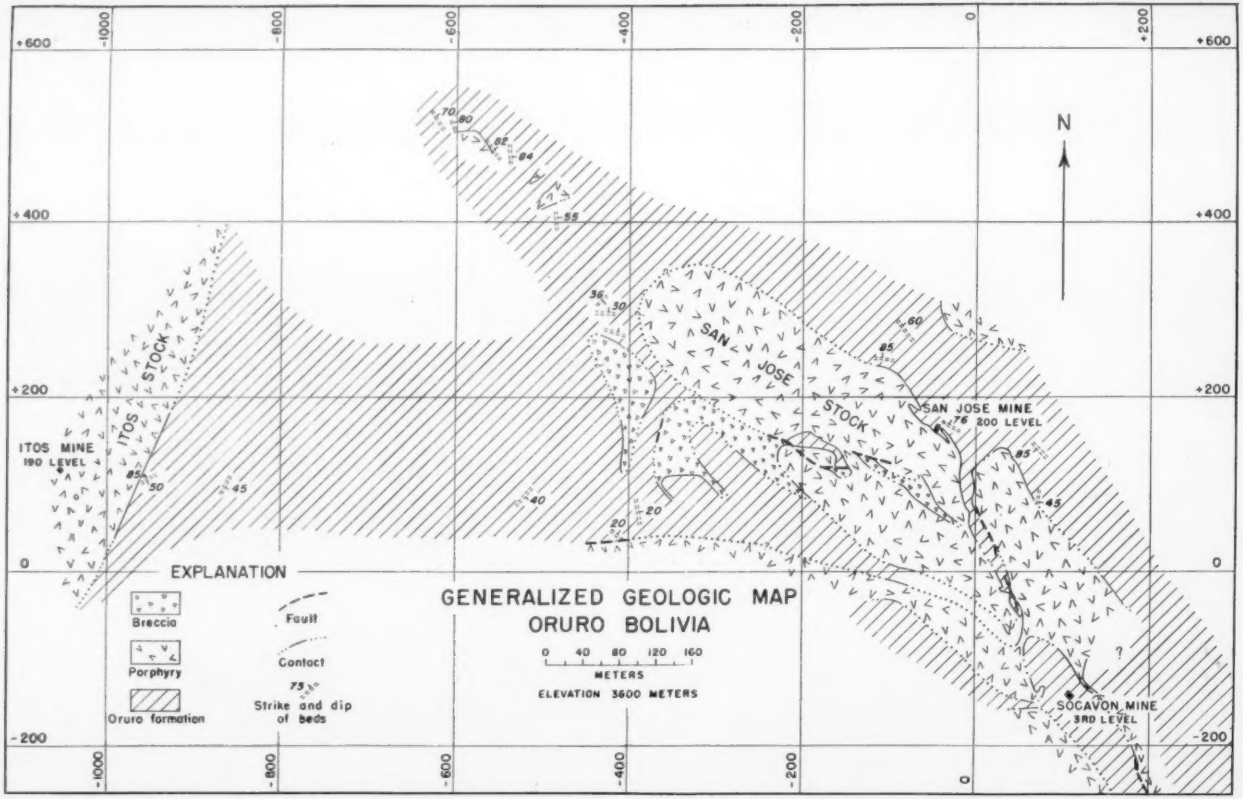

FIG. 8. Generalized geologic map showing the distribution of rocks on the –200 level of the San José mine and corresponding levels in the other mines.

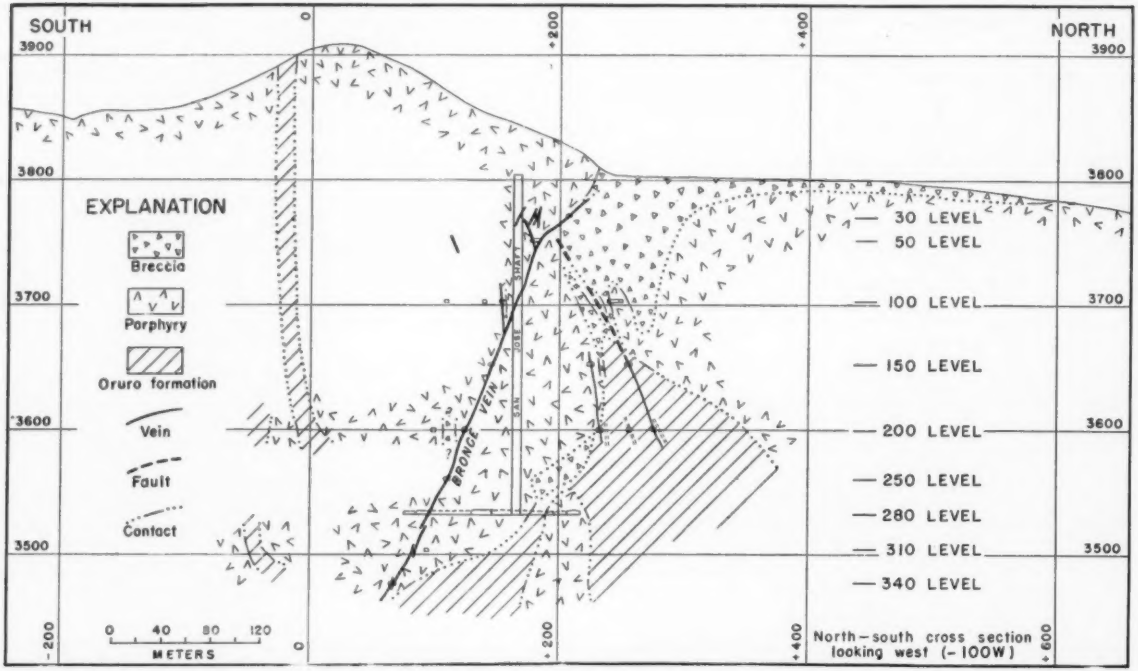

FIG. 9. Cross-section through the San José mine showing the distribution of rocks and veins. Section along north-south coordinate (– 100 W) looking west.

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FIG. 2. View of Oruro from the top of San Felipe mountain looking east across the altiplano toward the Cordillera Real. It is approximately 8 kilometers from site of picture to the lower slope of the mountain range.

FIG. 3. View looking south showing part of the "Cerros de Oruro" and altiplano in background. Eastern range of Andes is on horizon. The San José mine is midway up slope in right center. White buildings in the foreground are miners' homes.

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FIG. 4. San Pedro stock, looking north from San José mine. San Pedro mountain (center, horizon) is the second highest peak in the "Cerros de Oruro". (4010 m.)

FIG. 5. Viscachani stock. Looking north from the San José mine.

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FIG. 12. Tongue of quartz latite porphyry intrusive into argillite. Note irregular contact (white chalk mark), and inclusions of argillite in porphyry. A later breccia dike cuts both argillite and porphyry (lower left). Scale: Width of porphyry is 1.5 m; breccia dike, 4 cm wide. San José mine, 200 level, at shaft station. Looking vertically up at the "back".

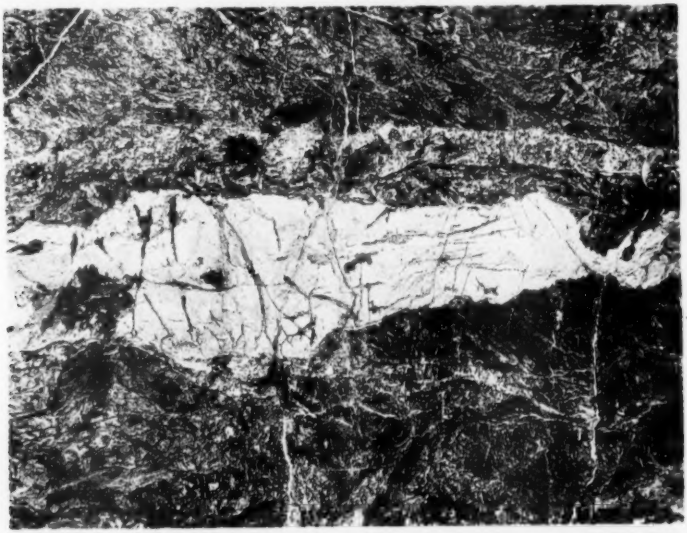

FIG. 13. A quartz latite porphyry sill intruding argillite parallel to bedding; maximum width 32.5 cm. A breccia dike, 10 cm wide, parallels the sill. San José mine, 250 level.

FIG. 14. The Itos stock from the Iroco hills looking east across the pampa. Conical hill is Cerro San Cristobal underlain by quartz latite porphyry of the Itos stock. Itos mine on right (south), and Santo Cristo mine on the front (west) side of the "cerro".

FIG. 15. A quartz latite porphyry dike, 4-5 m across, intrusive into Oruro formation in center. Bedding dips steeply away on both sides of outcrop and gradually flattens 10 m from outcrop. These relations suggest that the magma from which the dike was formed was injected under sufficient pressure to bend up the slate beds. In valley northeast of San José mine.

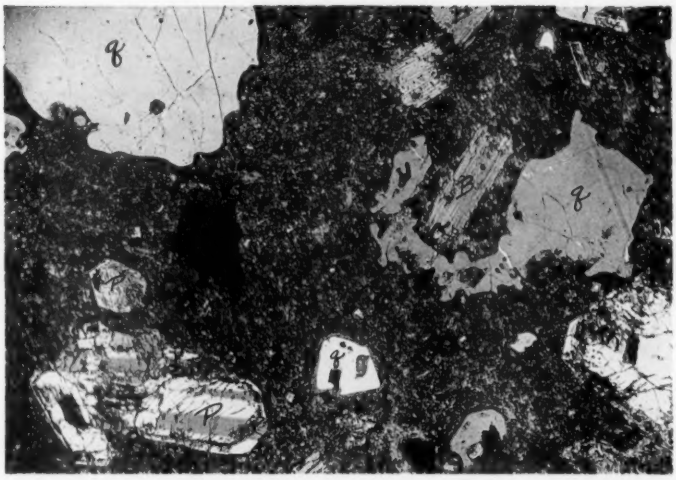

FIG. 16. Typical quartz latite porphyry. Note embayed quartz phenocrysts (q), frayed biotite (B), and sericitized plagioclase (P) phenocrysts. Groundmass is andesine with much kaolin and sericite. Surface, crest of San Pedro mountain. Thin section, × — nicols, × 22.

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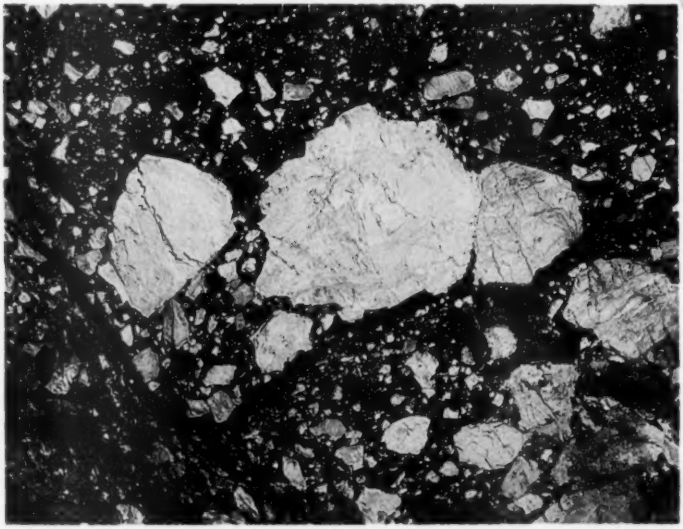

FIG. 17. Typical underground exposure of San José breccia on upper mine levels. Shape of fragments is characteristic; black argillite fragments are smaller than the porphyry. The black matrix appears to be finely pulverized argillite. Scale: largest white fragment is 60 cm across. San José mine, 50 level.

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FIG. 18. An underground contact between quartz latite porphyry and San José breccia. Note sharp contact, with no argillite inclusions in porphyry and no concentration of porphyry fragments in breccia at contact. San José mine, 50 level.

FIG. 19. Underground exposure of San José breccia with abundant porphyry fragments (white). Two stages of brecciation are evident. A small, black breccia dike of second stage is shown cutting across coarse fragments of first stage (left center). San José mine, 50 level.

FIG. 21. San José breccia showing nature and distribution of fragments. Porphyry fragments (P) are altered to sericite; argillite fragments (Arg) are an aggregate of sericite and kaolin; a parallel alignment of minerals is apparent, indicating that they are detrital grains rather than replacement products. Pyrite (black grains) is disseminated through the rock. San José mine, 75 level; stope above 100 level. X— nicols, X 24.

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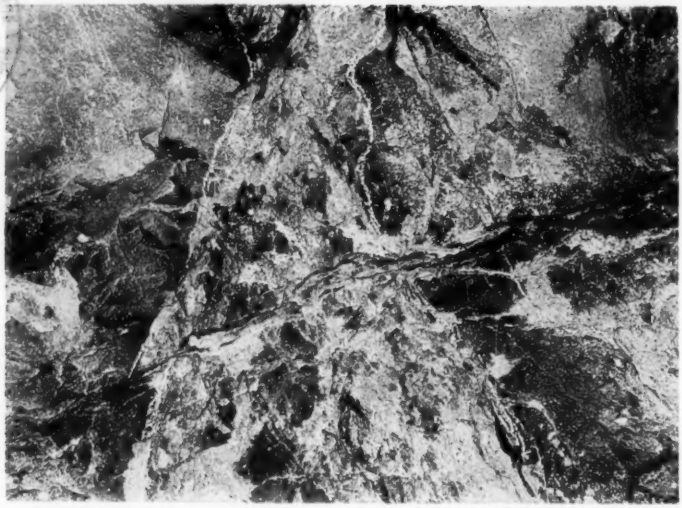

FIG. 33. Silver-bearing sulphosalt vein (dark gray) following a fracture which offsets a quartz-pyrite-cassiterite vein (outlined with white chalk). This indicates that fracturing took place during mineralization. Camera is 2.8 m distant. Silver vein is 1-3 cm wide; the pyrite vein is 40-50 cm wide. Location: -250 level, Ramos de la Plata section, San José mine.

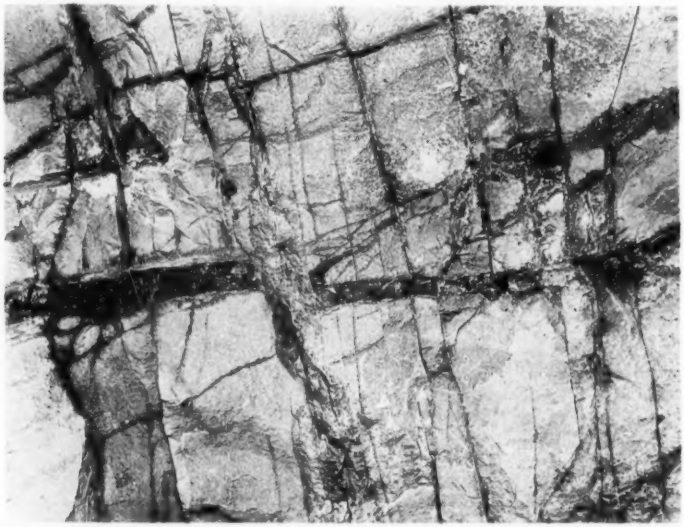

FIG. 34. Mineralized joints in Itos quartz latite porphyry along walls of San Luis vein. Horizontal breccia dike (black), 8 cm wide, has been offset along a joint. Joints are filled with andorite from paper-thin to about 1 cm wide.

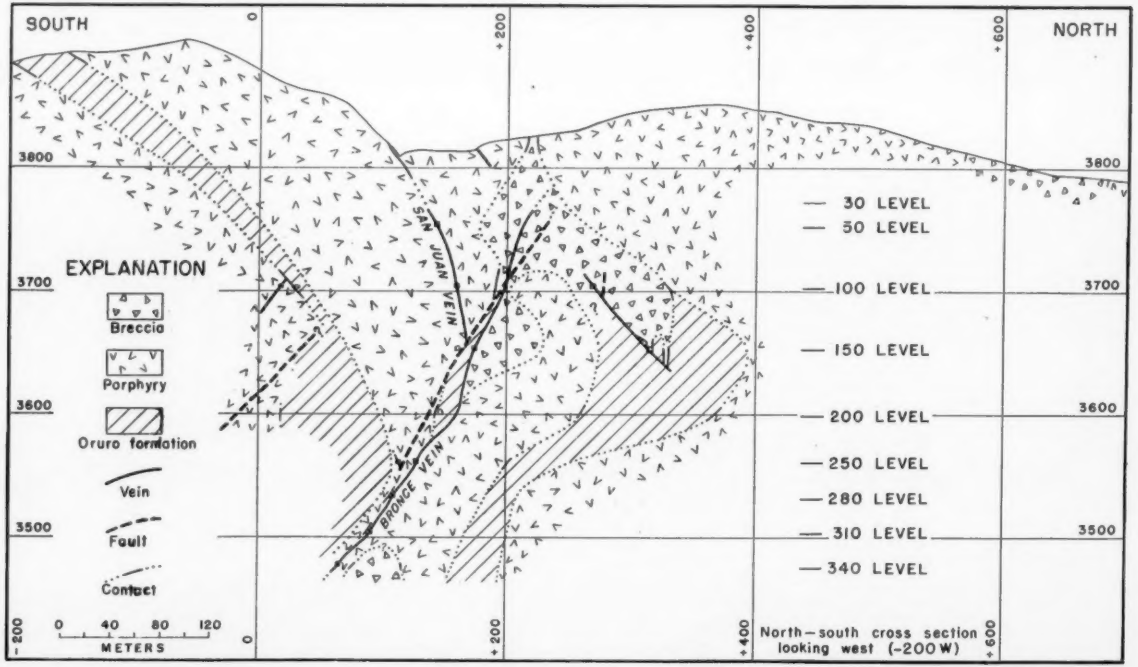

FIG. 10. Cross-section through the San José mine showing the distribution of rocks and veins. Section along coordinate line (— 200 W) looking west.

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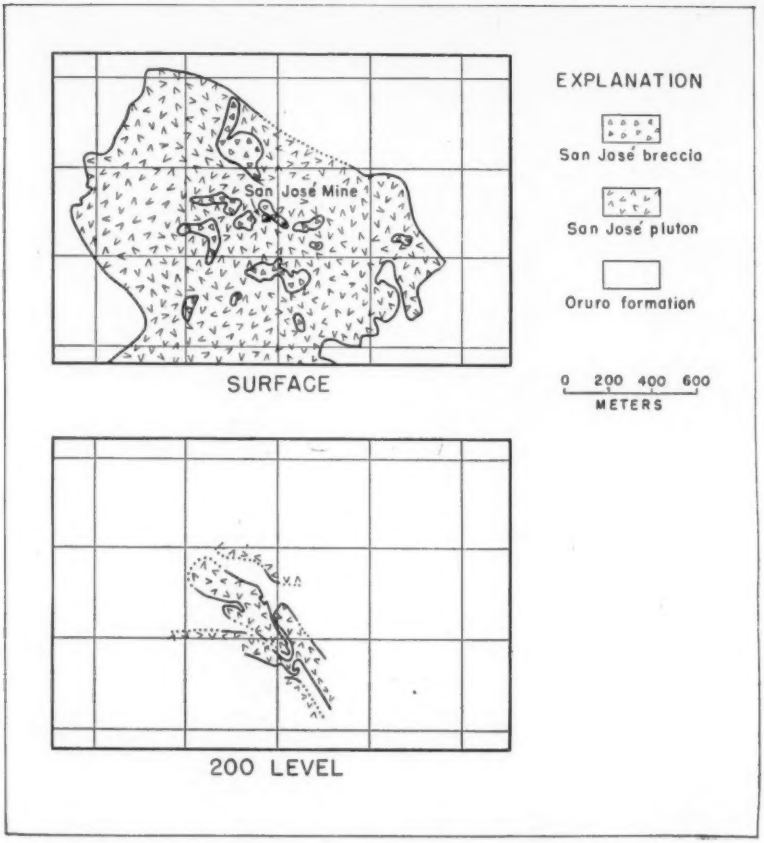

FIG. 11. Maps of the surface and a part of the –200 level, San José mine, showing the outline of the San José stock. (Dotted line indicates position of inferred contact.) On the –200 level the dike-like roots of the stock are shown. Much of the area on this level is occupied by the Oruro formation, but probably more porphyry exists beyond the present mine openings. The increase in amount of argillite with depth is apparent.

550 m long, although the position of the northwest contact is a matter of interpretation. On the present bottom level (–340 level), the porphyry is exposed in dikes only, but here the mine workings are not extensive. It is probable that much larger porphyry bodies exist beyond the present openings, but the tendency for the San José stock to contract in depth and to grade into feeding dikes is apparent. The structural form of the San José stock and its method of emplacement are considered in more detail later in the chapter.

The original outline of the San José stock was considerably modified subsequent to its intrusion into the Oruro formation by the formation of breccia along its contacts with the argillite. This resulted in rock bodies with very erratic shapes. The intrusive nature of the igneous rock is evident wherever porphyry and argillite are in contact (Figs. 12, 13). Apophyses of porphyry commonly extend into the argillite for several meters beyond the main intrusive body, and dikes and sills cut the sediments. Chilled contacts are generally absent. Occasionally, inclusions of argillite are in the porphyry close to the contacts, but nowhere are they large or numerous. In places, the porphyry contacts are conformable with argillite bedding, but in many other places are clearly discordant. The relations are illustrated in figure 8 by dip-and-strike symbols.

Itos Stock.—The Itos stock underlies San Cristobal Hill and the elongated ridge to the north and extends across West Viscachani Hill (Fig. 14). It thus occupies an area approximately 1,800 meters long and 500 meters wide. The eastern contact of the stock is well exposed throughout the Itos mine, where it is in contact with argillite and breccia. The average strike of the contact is N 20° E and the dip, 75° to 85° SE (Fig. 8). The extent of the stock underground is not fully known , but De Wijs considered it to be a dike-like body with a strike of N 30° E.[11]

Description of the Igneous Rocks.—The prevailing igneous rock of the Oruro Hills, both in the extrusive and intrusive bodies, is quartz latite porphyry. Although there are local variations in mineralogy, proportion and size of phenocrysts, degree of flowage orientation, and the amount of alteration, no detectable variation occurs of sufficient importance to justify the establishment of other rock species or the mapping of other geologic units.

Megascopic Description.—The quartz latite porphyry ranges in color from light gray to light green, and has prominent phenocrysts of quartz, feldspar, and biotite scattered through a fine-grained microcrystalline groundmass composed of small feldspar grains and laths. Round, vitreous quartz grains, 1.0 mm to 5 mm in diameter, are abundant throughout. The feldspar phenocrysts are usually prominent, varying from gray to pink in color, and obviously altered in all cases. They are predominantly plagioclase, usually andesine with lesser amounts of orthoclase. Biotite is abundant in many places in small flakes ranging in size from 2.0 mm across to grains seen only with the microscope. Campbell's estimate of the following proportions of phenocrysts is approximately correct: 60 percent feldspar; 20 percent quartz; 20 percent biotite.

In several localities, particularly in the Viscachani pluton and at the north base of San Pedro Hill, large euhedral phenocrysts of sanidine feldspar are numerous. They are considerably larger than the other constituents and average between 1.0 cm and 5.0 cm long, although in places they attain a length of 11.0 cm parallel to the c axis. They are twinned according to the carlsbad law and in places contain inclusions of biotite that are distributed within the sanidine in a pattern similar to that in the rest of the rock, suggesting that the sanidine formed by replacement of the solid rock.

Microscopic Description.—Under the microscope the rock proves to be holocrystalline with a distinct porphyritic texture. The phenocrysts are scattered through a very fine-grained intergrowth of feldspar, which in virtually all cases is highly altered. The porphyritic texture of the rocks, with the very fine-grained

[11] De Wijs, H. J., Private report to Compañia Minera de Oruro, Oruro, 1937.

groundmass, indicates that it is volcanic or hyperbyssal rather than plutonic in origin (Fig. 16).

Most of the quartz phenocrysts are well rounded and frequently deeply embayed. This feature is probably attributable to attack and partial solution by magma during the crystallization of the rock, possibly prior to or during injection. The coarse feldspar grains, though badly altered to sericite and kaolin, are predominantly andesine with an average composition close to Ab_{53} An_{47}. There is a variation of a few percent in the ratio of albite-anorthite molecules from place to place; in a few examples where zoned plagioclase phenocrysts were found, the more calcic zone is andesine, near the labradorite boundary, Ab_{60} An_{40} and the less calcic zone is on the oligoclase-andesine boundary, Ab_{70} An_{30}. Twinning is prominent in the plagioclase according to the albite and carlsbad laws. Biotite phenocrysts are common in brown, strongly pleochroic flakes. In a few cases magnetite rods intergrown with the biotite were observed. This mineral is altered to chlorite and red-brown hematite. The only accessory minerals noted were scattered needles and grains of apatite and zircon; the former mineral is relatively abundant in some sections.

The groundmass of the quartz latite porphyry is very fine grained, and alteration is so intense that it is difficult to determine accurately the minerals present or to describe the original texture. Microscopically, under high magnification, the groundmass appears to be made up entirely of feldspar. Some of the feldspar is andesine in well-defined laths or microlites, and some of it has an index below that of the quartz phenocrysts and is probably orthoclase or sanidine. It is difficult to determine the relative percentage of the two feldspar varieties, but a fair estimate would be about 50–50 (Fig. 16). The texture of the groundmass has been described as microgranitic, locally trachytic, and, in places where microlites are found, as pilotaxitic. The texture, in general, differs little from that of a rhyolite.

Several chemical analyses of the freshest Oruro rocks have been published by Kittl [12] and Jaskolski,[13] but in view of the alteration of the rocks the value of these analyses for classification purposes is somewhat doubtful. The average of three published analyses, when compared with the granodiorite and dacite, indicates that the Oruro rocks have about the same silica content as dacite and granodiorite; somewhat less Al_2O_3; less CaO than the granodiorite and more than the dacite; somewhat more Na_2O and somewhat more K_2O. The analyses are similar to that of the average dacite, but the greater amount of K_2O and smaller amount of CaO indicate that it is more alkalic than dacite and, therefore, nearer the composition of a quartz latite.

In summary, the average mineral composition of the Oruro intrusive rocks prior to alteration is estimated to have been 35 to 40 percent andesine, 25 to 30 percent sanidine, 20 percent quartz and 15 percent biotite. The average mineralogical composition of quartz latites and granodiorites is as follows: 30 percent alkali feldspar, 30 percent plagioclase feldspar, 20 percent quartz, and 25 percent dark minerals—biotite and hornblende. The Oruro rocks, therefore, have somewhat more plagioclase feldspar and somewhat less femic minerals than the usual quartz latite. Considering the porphyrytic texture, the very fine groundmass, the ratio of plagioclase to sanidine, the considerable amount of quartz and biotite, and finally the chemical composition, the rock may be classified as a quartz latite porphyry.

Extrusive Rocks.—Several areas of extrusive rocks occur in the Oruro district, but as far as is known, lava flows in the usual sense are not intimately

[12] Kittl, E., Análisis de rocas eruptivas de Bolivia: Revista Minera (Oruro), vol. 2, pp. 49–52, Feb., 1927.

[13] Jaskolski, S., Arch. de Minéralogie, Soc. Sci. Varsovie, vol. 8, p. 17, 1932.

associated with the ore deposits, and none has been recognized in the mines. Campbell mapped several areas of lava on the surface in the neighborhood of Cerro Santa Barbara, Cerro Serrato, and Cerro Guackallusta, and southwest of Cerro Santa Barbara. Also, Kozlowski and Jaskolski [14] described a small block of dacitic lava overlying shale on a small hill about 1 kilometer west of Cerro San Pedro. Other outcrops of extrusive rock may occur, particularly in the southern part of the Cerros de Oruro, but they have not been studied or mapped.

The lava flow that outcrops on the north slope of Cerro Guackallusta is 25 feet or more thick and has pronounced flow banding which is inclined 20° E. It is composed of light-gray, fine-grained quartz latite and, unlike the other quartz latite of the Oruro hills, is not porphyritic. Massive quartz latite porphyry, without banding, both underlies and overlies the Guackallusta flow. The field relations here indicate that both the massive rock and the flow-banded quartz latite are extrusives. However, on the east slope of Cerro Rubiales, these rocks appear to grade into massive porphyry which in depth is known to be intrusive.

On the basis of these observations, the conclusion seems justified that the lava flows on the outskirts of the San José stock, particularly those that underlie Cerro Guackallusta and Cerro Serrato, are probably the extrusive equivalents of the San José stock and probably formed contemporaneously with it.

In view of the geometric shape of the San José stock (dikelike in depth and with much greater horizontal extent on the surface), the problem naturally arises as to whether the upper extent of the stock is an intrusive or extrusive body. It certainly is not a lava flow, or assemblage of lava flows; but the mass as a whole, above the elevation where it changes from a dikelike body with definite intrusive relations to a broad shield or dome-shaped pluton, may be an extrusive body of an unusual type. The problem is considered further under the section on the method of emplacement of the igneous rocks.

Method of Emplacement of the Igneous Rocks.—The shape and general field relations of the intrusive bodies, the attitude of the associated lava flows, and the texture of the quartz latite porphyry indicate that the stocks and dikes of the Oruro Hills were near-surface intrusions. The fact that the intrusive porphyry bodies were, at least in part, contemporaneous with lava flows and at places grade into them, is additional indication that this conclusion is correct.

At least locally, forcible injection played some part during igneous intrusion. In several localities folding of the Oruro formation becomes more intense as the contacts between porphyry and argillite are approached, and in a few places the folded beds have been actually bowed upward by the force of igneous intrusion. A good example of this relation is illustrated in Figure 15.

The San José pluton is the only body sufficiently well known in three dimensions to warrant detailed consideration of its classification as a rock

[14] Kozlowski, R., and Jaskolski, S., op. cit.

body and its method of emplacement. The body has been called a stock, an ethmolith, and a laccolith, but its size, form, and structural relations to the surrounding sedimentary strata make usage of these terms questionable. Resemblance to certain volcanic bodies is suggested by the shape of the pluton, with feeding dikes flaring upward into a planoconvex body at the surface; by the abundance of post-intrusive breccia along its contacts, indicating explosive volcanic activity; by the absence of chilled contacts; and by the associated lava flows. Its resemblance to the intrusive stock at Llallagua is probably significant, although its volcanic affinities are not as pronounced as in that district. Concerning the origin of the stock at Llallagua, Turneaure [15] wrote as follows:

> The Salvadora intrusive is a cross-cutting body with the form of an inverted cone whose walls dip inward at steep angles. The abundance of breccia and the obscurity of chilled contacts indicate that explosive action was involved in its development; and these facts together with its form suggest a volcanic neck or crater.

There is considerable merit in the idea that the San José pluton, and possibly the other plutons of the Oruro district, similar to the body at Llallagua, are volcanic necks and occupy vents formed by explosive reaming.

Schmedeman,[16] in discussing the classification and characteristics of ore deposits associated with volcanic activity, has suggested the possibility that "the great majority of stocks and bosses under two miles in diameter, and many over that size, fill channels originally formed by explosive reaming." Daly,[17] Walker,[18] and Emmons [19] also have pointed out the possibility that certain igneous bodies occupy explosion vents. The mechanism by which stocks form in volcanic necks is not well understood, but some of the general features of the process may be noted. From the shape, contents, and relationships of such bodies, it seems probable that, during the rise toward the surface of batholithic magma, gas pressure builds up locally to such an extent that when confining pressures are exceeded, an explosion takes place forming a volcanic pipe or chimney. The circular hole or "diatreme" formed in this way is usually filled with broken rock fragments, and is sometimes, though not always, localized along a structural line of weakness, such as at the intersection of two faults. Subsequently, in certain places, magma flowed quiescently up into the pipe, cementing the breccia fragments with igneous rock. In other cases the breccia is penetrated by numerous dikes, but the rock fragments remain uncemented. The final stage of the process is observed where the explosion breccia is completely assimilated or displaced by a column of intrusive rock forming a volcanic plug or boss. According to Walker,[20]

[15] Turneaure, F. S., The tin deposits of Llallagua, Bolivia: Econ. Geol., vol. 30, p. 17, 1935.

[16] Schmedeman, O. C., Interrelated problems of volcanic activity and ore genesis: Ph.D. Thesis, Harvard Univ., pp. 51 and 61, 1937.

[17] Daly, R. A., Igneous Rocks and the Depths of the Earth, p. 102, 1933.

[18] Walker, R. T., Mineralized volcanic explosion pipes: Eng. and Min. Jour., vol. 126, pp. 895–898, 939–942, 976–984, 1928.

[19] Emmons, W. H., Diatremes and certain ore-bearing pipes: Am. Inst. Min. Met. Eng. Tech. Pub. no. 891, 1938.

[20] Walker, R. T., Op. cit.

explosion vents of this type are characterized by nearly vertical walls, vary from a few hundred feet to 3 miles in diameter, and are roughly elliptical in plan, although in detail they may be very irregular. Many examples of the association of ore deposits with volcanic necks or breccia pipes are known: Cripple Creek, Colo.; Cerro de Pasco, Peru; Braden, Chile; and Llallagua, Bolivia are well known occurrences. To this list may be added Oruro.

It seems probable that at Oruro explosive activity following a structural line of weakness developed a long narrow orifice, rather than the usual circular hole associated with diatremes, and that this orifice was later filled by quartz latite porphyry dike material. It is possible at Oruro that viscous magma rising through the elongated openings, now represented by dikes on the lower mine levels, extruded as viscous lava. On reaching the surface the lava spread laterally, giving rise to the transition, observable in the San José pluton, from intrusive to extrusive relations and resulting in a body with a horizontal cross-sectional area considerably greater on the surface than at depth.

In many places where ore deposits are associated with volcanic necks or pipes, pre-intrusive explosion breccias are a prominent feature. However, at Oruro, although there is much post-intrusive breccia, pre-intrusive breccias have not been recognized; and no evidence has been found of an early breccia, now cemented or assimilated by quartz latite porphyry. It is possible, of course, that such a breccia existed and was entirely assimilated or replaced; or that, in fact, it does exist and has not been recognized.

The San José Breccia.

The youngest consolidated rock of the district is a coarse breccia composed of subangular to rounded fragments of light-gray altered quartz latite porphyry and dark argillite in a black matrix of fine-grained, pulverized argillite. The fragments range in size from a few millimeters to one meter or more in diameter, with the porphyry uniformly larger than the argillite pieces. They are irregularly distributed through the matrix with no suggestion of sorting, bedding, or flow structure (Figs. 17, 18, 19).

The San José breccia,[21] named for the mine where it is best exposed, is found only in the vicinity of the mines, where it occurs in dikes, lenses, pipes, and irregular bodies. It has a decided tendency to follow the contacts between porphyry and argillite, although crosscutting bodies are common. Breccia bodies have not been found in the argillite or in the quartz latite porphyry far from their mutual contacts, but not all parts of the contacts have breccia bodies. Figures 8, 9, and 10 show the typical outline of the masses in plan and section. Clastic dikes are present locally cutting the larger breccia masses, indicating that brecciation occurred in two stages.

A definite relationship between size and distribution of fragments and porphyry-argillite contacts is observable in several crosscuts through the breccia bodies in the San José mine. In many places, the broken pieces of por-

[21] The term "explosive" breccia used by Campbell for this rock may be somewhat more descriptive, but a noncommital term seems better than one which indicates a mode of origin that may be debatable.

phyry increase in number and size toward the igneous rock bodies, whereas toward the argillite, they decrease until the breccia is made up entirely of pulverized argillite. The contact with porphyry is sharp, but usually it is difficult to place accurately the limit between argillite and breccia unless stratification is unusually prominent in the sediments. The comminuted argillite does not differ in appearance from argillite with a uniform texture and no bedding. A similar gradational relation and distribution of fragments has been observed vertically in the mines. Toward the surface the fragments increase in size and number. In the smaller breccia masses gradational relations are not present.

The largest and most noteworthy breccia body in the district is a pipe that outcrops on the east slope of Todos Santos Hill, a short distance from the San José mine office, and which has been traced 300 m down through the mine to the − 200 level. Figure 20 is a block diagram of this breccia pipe and illustrates the outline and vagaries of the breccia masses.

Microscopic Description.—Under the microscope, the clastic nature of the breccia is clearly seen (Fig. 21). The porphyry fragments are subangular and are highly altered to quartz, sericite, and pyrite. The argillite pieces are less clearly defined, but are in places distinctly broken. The dike matrix is a very fine-grained aggregate of detrital quartz grains and sericite with an abundance of carbonaceous material, probably derived from the disintegration of the argillite. In places, a flow structure is present, suggesting movement of particles during emplacement, although flowage lines or parallel alignment of fragments are not apparent megascopically. The matrix contains no trace of igneous material, and therefore, is nonigneous in origin; *i.e.*, it is not congealed magma.

Relative Age of the San José Breccia.—It has been generally agreed that the San José breccia is younger than the Oruro formation and the quartz latite porphyry intrusive bodies. This conclusion is based on the composition and structure of the breccia, the distribution of the porphyry fragments, and the intrusive relations where the breccia cuts the porphyry bodies in dikes, sills, irregular apophyses, and pipe-like bodies. There is no suggestion of porphyry intruding breccia, nor is there any evidence that igneous material forms the cement or matrix of the breccia.

Origin of the San José Breccia.—Breccia bodies somewhat similar to those at the San José mine occur in many other mining districts, notably at Llallagua, Bolivia; Casapalca and Morococha, Peru; Sudbury, Ontario; Nagyag and Verespatak, Hungary; and Cripple Creek, Colo., especially the Cresson blowout. According to Turneaure,[22] the similarity of the San José breccia to the post-intrusive breccia is striking. At Llallagua, large masses of coarse breccia occur along the margin of the Salvadora stock and well within its border. Furthermore, black clastic dikes, similar to the second-stage breccia dikes at Oruro, cut the white porphyry of the stock. The fragments and matrix of the breccia at Llallagua resemble closely those at Oruro except that those associated with the Salvadora stock are more intensely altered with about 80 percent of the mass having been converted to black tourmaline.

[22] Personal communication. Details of the Llallagua breccia are described in "The tin deposits of Llallagua, Bolivia": Econ. Geol., vol. 30, no. 1, p. 19, 1935.

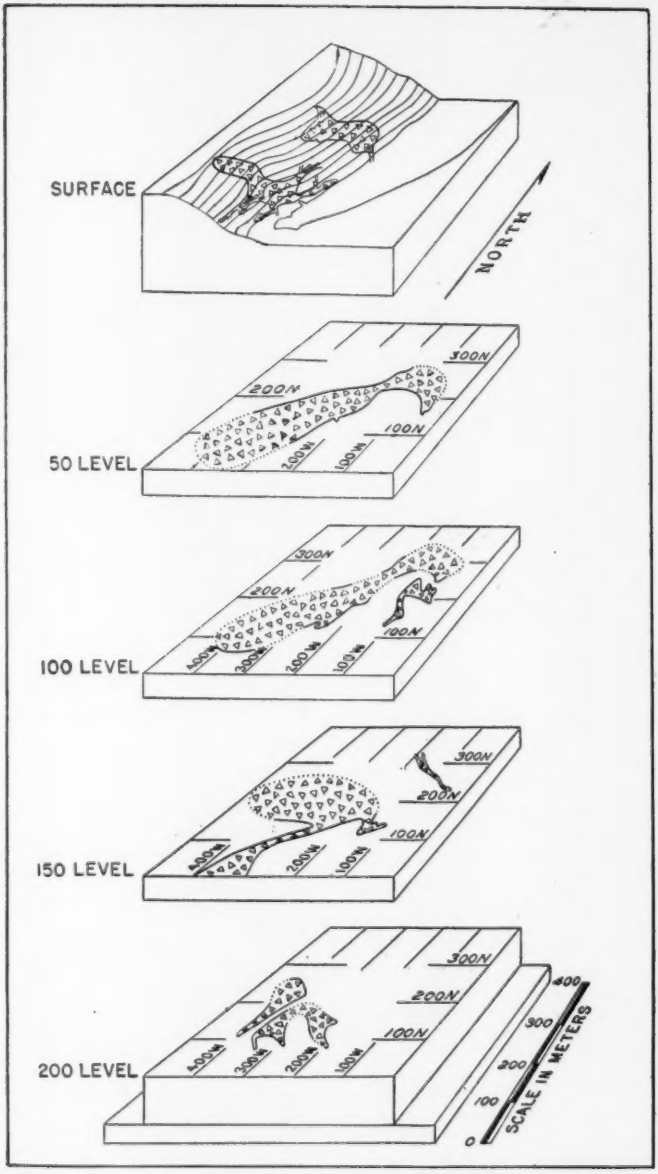

FIG. 20. Block diagram showing the outline of the San José breccia pipe. The blocks are arranged to show the relative position and shape of the pipe on the surface and on several mine levels.

Numerous explanations have been given for the origin of the San José breccia. The resemblance of these breccias to those formed in connection with volcanic activity is striking, and formation under near-surface conditions by explosive forces more nearly accounts for the facts than any other explanation. It is most probable that the breccias formed by explosive activity, which followed lines of weakness parallel to rock contacts and subsidiary fractures, and caused shattering of the wall rocks along fissures and violent churning of the broken rocks, thus rounding the fragments and enlarging the channelways. Probably, the explosive force extended to the surface, propelling some of the fragments before it and scattering débris over the surrounding region. Possibly some of the fragments settled back into the pipes; but the attitude, position and shape of many of the bodies indicate that they were not all exposed to the surface and could not represent fillings of cavities thus exposed.

Many of the smaller, more persistent dikes suggest that they were formed by the intrusion of a "mudlike" mass under high pressure, possibly accompanied by magmatic water.

The source of the explosive force is a matter of interesting speculation. The breccias were formed somewhat later than the intrusion and solidification of the quartz latite porphyries, and prior to the flow of mineralizing solutions that formed the ore bodies. It is probable that these were closely related phenomena, and that they had their origin in a magma chamber at depth, from which the porphyry magma, the force of brecciation, and later the ore solutions were given off. The sudden release and escape of pent-up gases under high pressure would undoubtedly have resulted in the shattering of country rock, the churning of rock fragments, and the formation of breccia bodies of the San José type.

THE ORE DEPOSITS.

The tin-silver ore deposits of Oruro occur in a complex group of veins which occupy a belt roughly 2,000 m long and 1,200 m wide (1.24 × 0.75 miles) trending N. 60° W. across the central part of the "Cerros de Oruro." The lease boundaries of Compañia Minera de Oruro, shown in Figure 6, roughly outline the mineralized area.

Two distinct types of ore bodies occur in the Oruro district, and although they are gradational in character, they have a distinctly different mineralogy and occurrence that require different mining methods and different metallurgical processes. These types are:

(a) primary sulphide ore bodies mined for their silver and tin content by underground methods. Small amounts of copper and lead have been produced from this source in the past, and during World War II considerable antimony was recovered.
(b) "pacos" or oxidized ore bodies, formerly rich in silver, but now mined for their tin content alone by open-cut methods at the surface and to a lesser extent in shallow underground workings.

(a) The primary sulphide ore bodies are found in veins in the San José and Itos quartz latite porphyry stocks, or contiguous to them, and occur geo-

graphically in four clusters, each of which is a center of mineralization and is characterized by a distinct fracture system that extends to an appreciable depth. The four major clusters are:

(1) San José cluster
(2) San Luis cluster
(3) La Colorada cluster
(4) Tetilla cluster

Although the grouping of the Oruro veins around definite centers is not readily apparent on the surface, where many fractures and veins are scattered at random through the mineralized area, on the lower mine levels the clustering is readily discernible. Three of the vein clusters are shown clearly in Figure 22, a generalized map. The fourth cluster lies to the south and is no longer accessible.

The veins of each cluster form a complex system, differ greatly in persistence, and vary in width and structural detail. The longest veins, the Purísima, the Bronce, and the Carnaval-Moropoto, have been followed 500 m horizontally. The Bronce vein has been mined to a vertical depth of 400 m below the outcrop; the San Luis vein to a depth of 600 m. The others are less extensive. The veins themselves are relatively thin tabular bodies and usually have well-defined walls, but in many places the end of ore is an "assay limit." The average mining width throughout the district is less than one meter, but in a few places stopes as wide as 15 m have been mined, particularly on the San José and San Luis veins. Ore tends to occur in clearly-delineated shoots, but many bodies of mineable ore grade along their strikes into vein material too poor to be worked.

During the period from 1930 to 1940, the primary sulphide ore was the major source of supply and yielded the greater part of the tin and silver production of the district. However, with the exhaustion of the primary ores in recent years, they have been the source of only about 50 percent of the tin mined, although they continue to be the sole source of silver in the district.

(b) The pacos ore bodies form a part of the capping or thin blanket of oxidized rocks covering the surface at the outcrop of the major veins. The ore is found in pockets, irregular bodies, and a multitude of small veinlets and extends to variable depths below the surface, depending upon the depth of oxidation. The veins, noticeably, have been oxidized considerably deeper than the adjacent wall rocks. The small, narrow veins are oxidized not more than 25 m in places, whereas the large, persistent veins have been affected by surface agencies down to 150 m below the outcrop in the deepest places.

During the Colonial period, the pacos ores were mined for their silver content alone, and tin was ignored. Now the bonanza silver ores are exhausted, and tin is the only product. In spite of many years of intensive exploration, these ores still yield a substantial tonnage, and during the past five years have accounted for about half of the tin ore mined.

The Vein System.

The ore deposits of Oruro formed partly by open-space filling and partly by replacement along a complex system of pre-mineral fractures. The min-

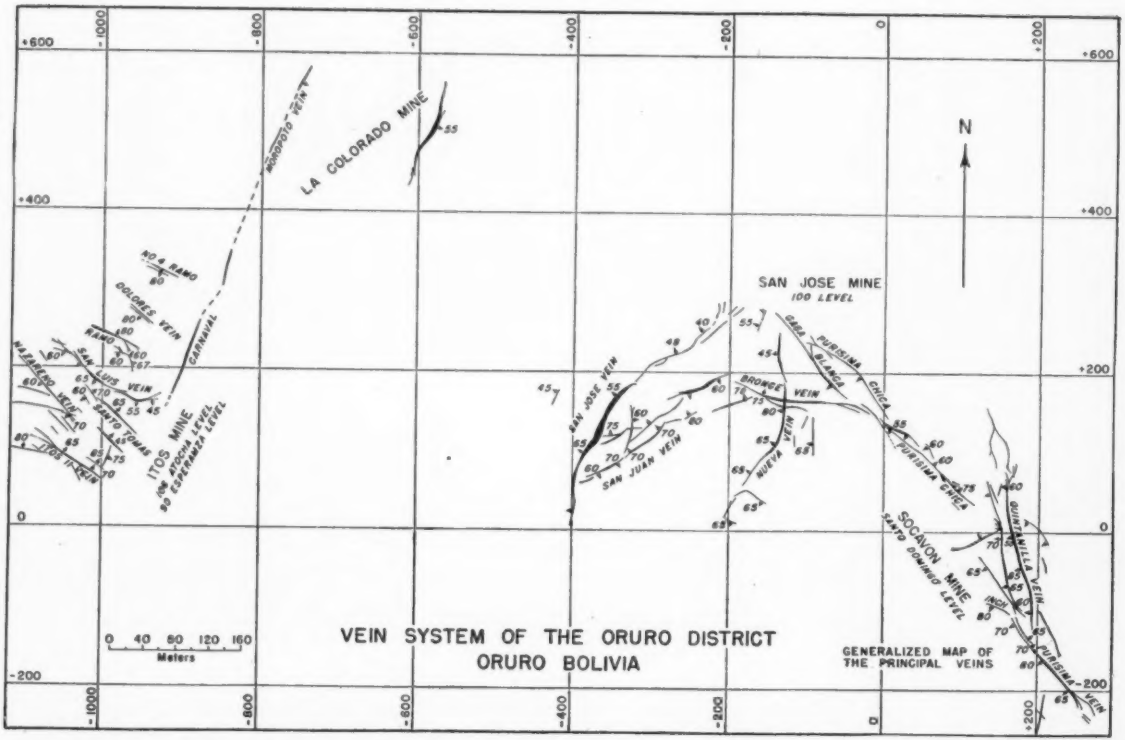

FIG. 22. Generalized map of the principal veins on a well-developed mine level. Note that the veins form three clusters. The eastern group is found in the San José and Socavón mines, the western group in the Itos mine, and the northern group in the Colorada mine. A fourth group, the Tetilla, is outside the map area.

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eralization coincides with a block of ground in which the rocks have failed along numerous complex fractures, intricate in detail, yet systematic throughout the district. In their double function as channelways for ore-bearing solutions and as loci for deposition these fractures governed the position, shape, and size of the ore bodies, and, therefore, may be properly regarded as the structures most capable of direct service to the mining geologist in the search for new veins and ore shoots. The distribution of the veins was governed by the pre-ore fracture pattern, and the localization of tin and silver in rich ore shoots along individual veins was determined to a large extent by minor structural features along the specific breaks.

Although mapping of the details of each fracture zone and its classification into a distinctive system may lead to empirical results of practical value, an adequate understanding of these features is not likely to be attained until they can be correlated with the regional deformation, and until some measure of understanding is attained of the behavior of the rocks in the given assemblage when subject to stress. An effort toward such a correlation is made in this study, though it is realized that our present knowledge hardly justifies more than tentative opinions regarding the stresses inferred from the observed strains.

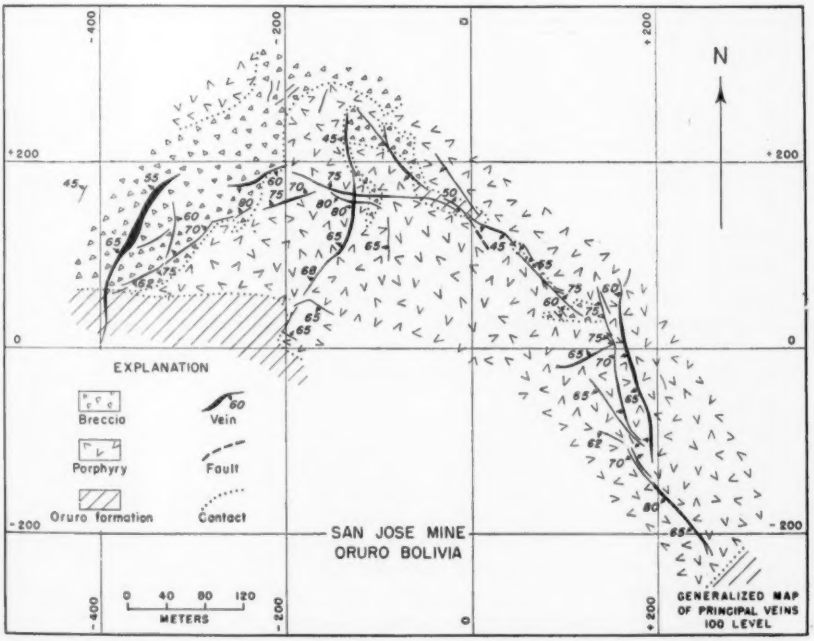

FIG. 23. Generalized map of the principal veins on the –100 level, San José mine, and the corresponding level of the Socavón mine.

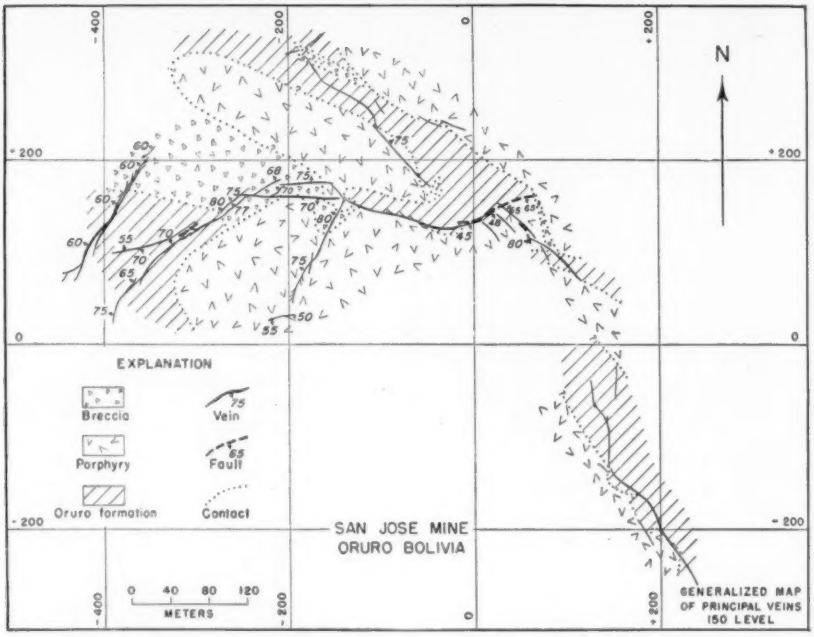

FIG. 24. Generalized map of the principal veins on the –150 level, San José mine, and corresponding level of Socavón mine.

The distribution and general pattern of the veins on a well-developed mine level are illustrated in Figure 22. The series of illustrations, Figures 23, 24, and 25, shows the veins on three successive mine levels; and, although the veins differ considerably in structural detail on each level, the general grouping and attitude of the structures are persistent from level to level. The general characteristics of the Oruro fracture system are described in some detail in the following pages.

(1) *San José Cluster.*—This group is made up of some of the largest, most extensive veins of the district and includes the Purísima, Inch, Quintanilla, Rasgo, Purísima Chica, Bronce, Nueva, Alacranes, San Isidro, San Juan and San José veins. These occur in a broad arc-shaped area, convex to the north with the prominent veins swinging in a broad arc from a northwest strike at the southeast to a southwest strike at the northwest.

(2) *San Luis Cluster.*—In the Itos mine, 550 m to the west of the San José cluster, is the San Luis vein group. This is a set of subparallel veins with a general northwest strike, roughly at right angles to the strike of the contact between the Itos stock and the Oruro formation (Figs. 26, 27).

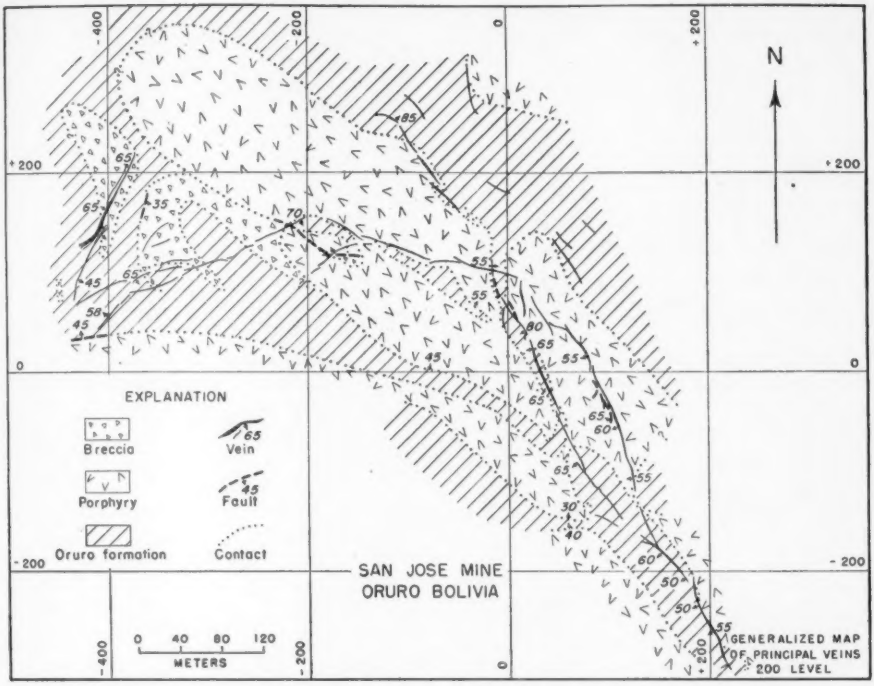

FIG. 25. Generalized map of the principal veins on the –200 level, San José mine, and corresponding level of Socavón mine.

Three well-defined vein sets occur in the San Luis cluster. The first and most important strikes N 40°–60° W and dips both north and south 45°–80°; it includes the San Luis vein, one of the most productive veins of the district, as well as the Dolores, Santo Tomás, Nazareno, Itos II, Ramo II, and Ramo IV. The second set strikes N 70°–80° W and dips 70°–80° N. Several strong structures and many joints are included in this set, but no important veins. The third set strikes N 25° E and dips 55°–70° N, parallel to the contact between the Itos stock and the Oruro argillite. Only one important vein, the Carnaval, occurs in this group, and this follows the rock contact very closely. Minor fractures and joints, a few of which are mineralized, also are included in this set.

(3) *La Colorada Cluster.*—A parallel group of veins striking uniformly north-northeast (N 20°–25° E) and dipping 55°–60° southeast occurs in La Colorada mine. The Grande and Moropoto veins are important members of this cluster. The Moropoto vein may be considered the northeast extension of the Carnaval vein in the Itos mine, and, similarly, follows the rock contact.

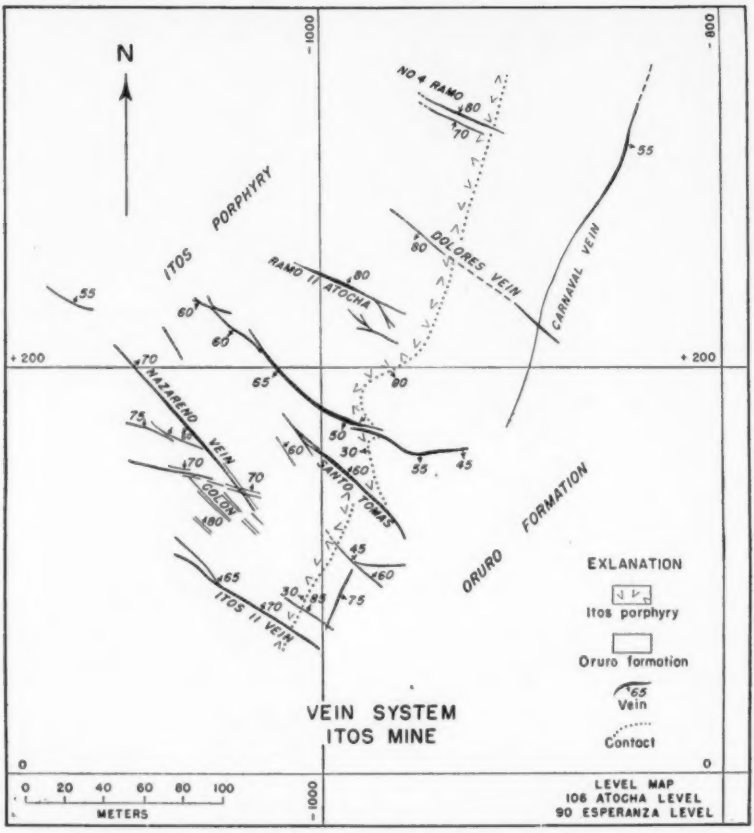

FIG. 26. Map of the 106 Atocha and 96 Esperanza levels of the Itos mine showing the principal veins and their relation to the contact between the Itos stock and the Oruro formation.

The veins of this cluster become more complicated and increase in number near the surface and include the Amarilla, Amarilla II, Lindero, and Grande II veins, all of which join the Grande vein in depth.

(4) *Tetilla Cluster.*—The fourth vein cluster is on the east and south slope of Tetilla Mountain (Fig. 6) about one kilometer south of the other groups.[23] The extent and characteristics of the veins worked here during the Colonial period are not known, as the mine has been abandoned for many years. However, a map published by Wiener shows a long adit which cuts

[23] Wiener, P. M., Les mines d'argent d'Oruro, Bolivie: Annales des Mines, ser. 9. T. 5, pp. 511–520, 1894.

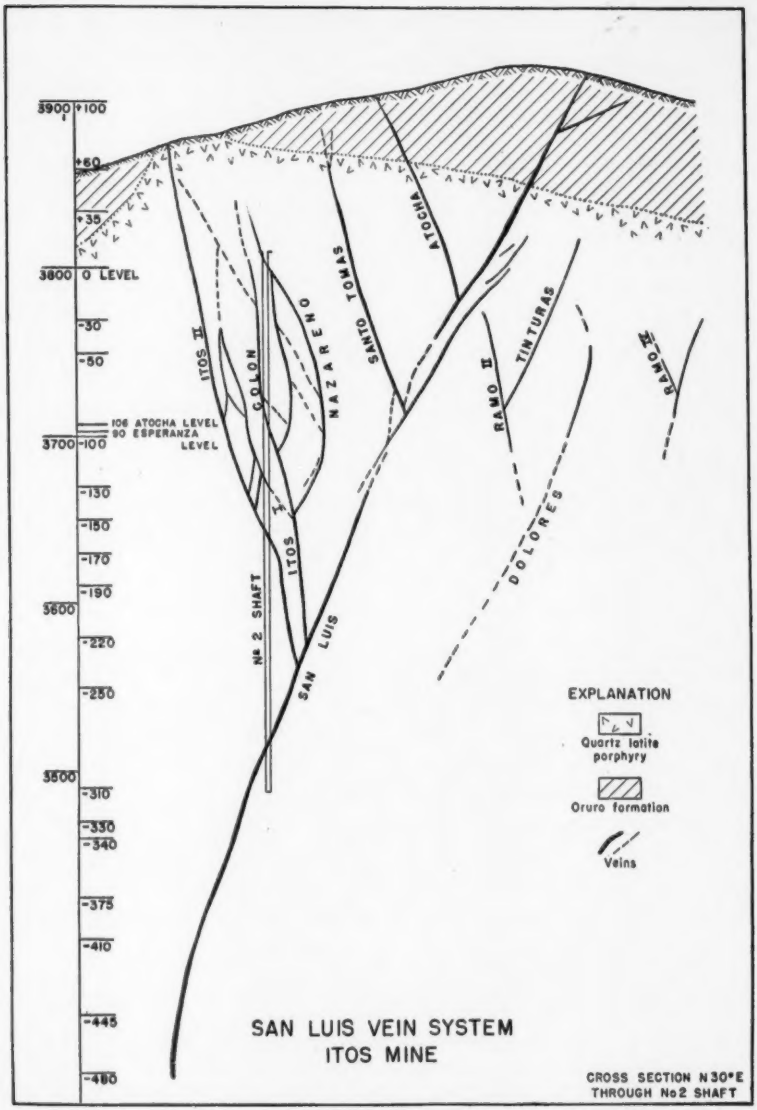

FIG. 27. Section through the Itos mine showing the vein pattern. Although in cross section the veins with opposite dip appear to form a conjugate pattern, they diverge 30° to 40° in strike and, therefore, are not truly conjugate. However, individual members of the cluster are conjugate, with parallel strikes and opposite dips. (Modified after Backels and Campbell.)

eight veins in a distance of about 625 m. These veins apparently strike from N 15° W to N 25° E.

Besides the major vein clusters, numerous small veins which have been worked near the surface are scattered throughout the mineralized area. These veins do not persist in depth, and although the vein fractures undoubtedly were due to the same stresses that caused the major fracture systems, it is not readily apparent, except from their geographic position, with which of the vein clusters they are allied.

Relation of Veins to Porphyry Bodies.—The attitudes of the veins show a fairly consistent relationship to the shape, direction of elongation, and contacts of the quartz latite porphyry bodies with which they are associated. In general, one set strikes parallel, and another at right angles to the elongation of the porphyry stocks. In the Itos mine this relationship is particularly well shown (Fig. 26). The major group, including the San Luis vein, strikes normal to the contact and another group, represented principally by the Carnaval-Moropoto vein, is parallel to the long direction of the stock and for a considerable distance is actually on the contact between porphyry and argillite.

In the San José and Socavón mines a similar relationship is shown, though here the pattern is complicated by the irregularities of the intrusion and the intervening bands of argillite (Fig. 25). Most of the veins in these mines are parallel to the long direction of the porphyry bodies. Another set, including the Rasgo, Nueva, and San José veins, however, strikes at right angles to the elongation.

On the upper levels and surface, the igneous rock bodies have a roughly elliptical outcrop pattern without a pronounced extension in one direction. Therefore, the relation is not apparent. However, the strike of the veins on the surface is the same as in depth and is probably determined by the shape of the porphyry bodies on the lower mine levels.

Each of the three wall rocks, porphyry, argillite, and breccia, behaved differently under stress; and failure produced fractures with markedly different characteristics, depending upon the rock type in which it occurred.

In fracturing, the quartz latite porphyry behaved as a brittle rock. Through-going lines of fracture were formed in it and resulted in the complex vein pattern. At the surface, most of the known veins are in the porphyry, but in depth the relation is less clear, although there is some reason for believing that the veins are never far from porphyry.

Contacts between porphyry and argillite, and porphyry and breccia were favorable places for the formation of strong fractures. In many places veins follow contacts, as an inspection of the level maps will verify. Parts of the Purísima, Inch, and Bronce veins are on contacts parallel to the long direction of the quartz latite porphyry plutons. The Carnaval-Moropoto vein in La Colorada mine follows an argillite septum between two porphyry bodies for a long distance, but in depth the fractures flatten and depart from the contact. The ore bodies of the Itos mine were localized at the east contact of the Itos quartz latite porphyry stock and are almost entirely on the porphyry side of the contact.

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The argillite, shale and slate of the Oruro formation generally behaved incompetently during the deformation that produced the pre-mineral fractures, and yielded more by plastic deformation than by fracturing. Through-going lines of fracture in it are not common, except in a few places. Faults in the argillite are usually irregular and discontinuous, and tend to dip more flatly than in other rocks.

Fractures passing from porphyry into argillite at the contact generally change in strike, flatten in dip, and die out in a short distance in the argillite. This is well illustrated by the San Luis vein where it extends from the Itos stock into argillite. Singewald and Miller[24] noted the tendency for veins to die out in argillite and described one example as follows:

> The Rasgo vein runs into slate and changes its character completely at the contact, for, whereas in the porphyry it is a well-defined vein rich in tin, in the slate it splits up into a number of minute stringers less than 1 cm. wide, which carry no cassiterite or iron sulphides, but consist entirely of the argentiferous sulphantimonides carrying 1 or 2 percent silver.

The Grande vein below the − 116 level, La Colorada mine, is an exception to the general rule because it is entirely in argillite, and is still a strong vein 60 m beneath this level. However, in this case, the argillite is hard and brittle, probably from contact metamorphism. As far as is known, no other vein occurs in the hard, massive argillite.

The San José breccia cracked with ease, and many veins are found in it. The breccia itself does not appear to be a brittle rock, and, therefore, as the breccia bodies are relatively small and are found only near the porphyry, its tendency to fracture readily probably reflects the influence of the brittle porphyry. Many fractures follow closely the contact between porphyry and San José breccia, probably indicating that the contact areas were lines of structural weakness. Numerous other veins crosscut breccia bodies at right angles to their contacts with prophyry. This is especially noticeable on the upper mine levels and on the surface, where both the Moropoto and Grande veins traverse breccia for over 100 m.

The San José vein is a good example of a strong fault zone crosscutting San José breccia for a relatively long distance. On the − 100 level it cuts breccia for over 200 m before entering slate, whereas on the − 200 level it follows breccia for over 75 m before passing into the Oruro formation and dying out in a "horsetail" zone.

Strike and Dip Groups.—When the veins of the three clusters are considered independently of their enclosing rock bodies, it is found that they strike at all azimuths. However, it is possible to classify them roughly into two strike groups. The two directions, N 30°–60° W and N 20°–60° E, include all of the important veins.

The veins range in dip from 40° to vertical with the average between 55° and 60°. Dips flatter than 40° are rarely found. The individual veins vary considerably in inclination from place to place, and some reversals in dip are found.

[24] Singewald, J. T., Jr., and Miller, B. L., Mineral Deposits of South America, pp. 110–114, New York, 1919.

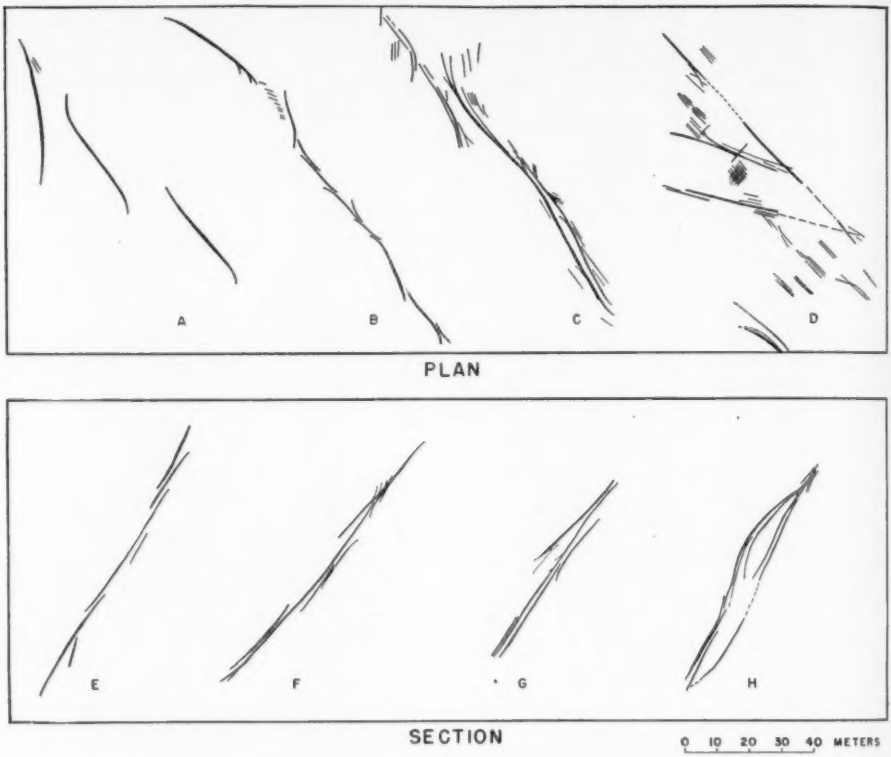

FIG. 28. Types and characteristics of the pre-mineral fractures that guided ore deposition in the Oruro district are shown in plan and section.

A. *Shingle Structure.* Map of a part of the Purísima vein on the –200 level, San José mine, showing two flat S-shaped and one arc-shaped fracture arranged en échelon. These fractures are a combination of shear and tension breaks; the main part of the fractures formed by shearing, but where they curve from the average trend, failure was due to tension.

B. *Shingle Structure.* Map of another part of the Purísima vein on the 3rd level of the Socavón mine where the vein follows a series of overlapping, en échelon fractures with several flat-S, reverse-S and arc-shaped breaks. The individual fractures are a rather short, discontinuous succession of shear breaks that curve into tension fractures and die out. In one case where a shear fracture curves from its average strike, it dies out in a "horsetail." In another place, a series of short, parallel tension fractures occupy the en échelon gap between two shear planes.

C. *Shingle Structure.* Map of the pre-mineral fractures that controlled mineralization on the –200 level, San José vein. Here the vein follows a relatively strong, persistent, curving shear break with numerous subordinate parallel shears.

The Vein Types.

The pre-mineral fracturing resulted in several distinctive vein types; and, in order to appreciate their structural vagaries, it is necessary to study the details of the early fracturing in three dimensions and to recognize their characteristics in both plan and section. The types and characteristics of the pre-mineral fractures that guided ore deposition in the Oruro district are shown in plan and section in Figure 28.

Throughout the mineralized area, the pre-mineral fractures form a surprisingly consistent series of curving faults, generally arranged en échelon. Single breaks rarely extend the length of a vein, but the mineralization usually follows the course of a succession of parallel, curving, and overlapping cracks which split and die out within a short distance from where they bend away from the average trend. Individual fractures are found with a variety of shapes; very flat-S or reverse curves, reverse S's, and arc-shaped cracks are the most common.

The pre-mineral fractures are usually well defined, and along their straight parts, the walls are readily followed. They are usually polished smooth and commonly have striae, mullion, and gouge along them. The shape of the fractures, with the striae and gouge along them, is indicative of shear breaks; and the straight parts of the fractures probably formed by shearing. Where the shear planes curve from the average trend and die out, failure was probably caused by tension. Characteristic tension fractures, such as "horsetails," and short, closely spaced, parallel breaks, forming sheeted ground at an acute angle to the trend of the main fracture, are common.

The individual units of the pre-mineral fracture pattern range in horizontal length from a few centimeters to 100 m. The main break of the San José vein on the –100 level is 100 m long, whereas elsewhere in the vein none of the fractures can be traced farther than 30 m. The unit fractures are more persistent down the dip than along their strike. The longest one that was measured along the dip forms the hanging wall of the San José vein between the 75 Intermediate and the –150 levels in the San José mine. It was traced continuously through the stopes from level to level for 95 m. A

As the main shear dies out along the strike, it curves into a "horsetail" zone of tension fractures.

D. *Sheeted Structure.* Map of 90 Esperanza level, Itos mine, showing "sheeted" veins. The pre-mineral fractures are sheeted breaks, closely spaced, straight, and parallel, as in a typically sheeted rock.

E. *Shingle Structure.* Cross section through the Grande vein showing the shingle structure to best advantage. The pre-mineral fractures form a series of overlapping, en échelon breaks arranged like the shingles on a roof. In going up the dip, as one fracture dies out, another appears in the hanging wall across an en échelon gap. Subparallel fractures occur in the footwall of the main fractures.

F. *Shingle Structure.* Section through the Bronce vein showing a variation of the "shingle" structure.

G. *Shingle Structure.* Section through the Purísima vein showing characteristic en échelon and "shingle" structure of pre-mineral fractures.

H. *Loop Structure.* Section through the Bronce vein, showing "loop" structure.

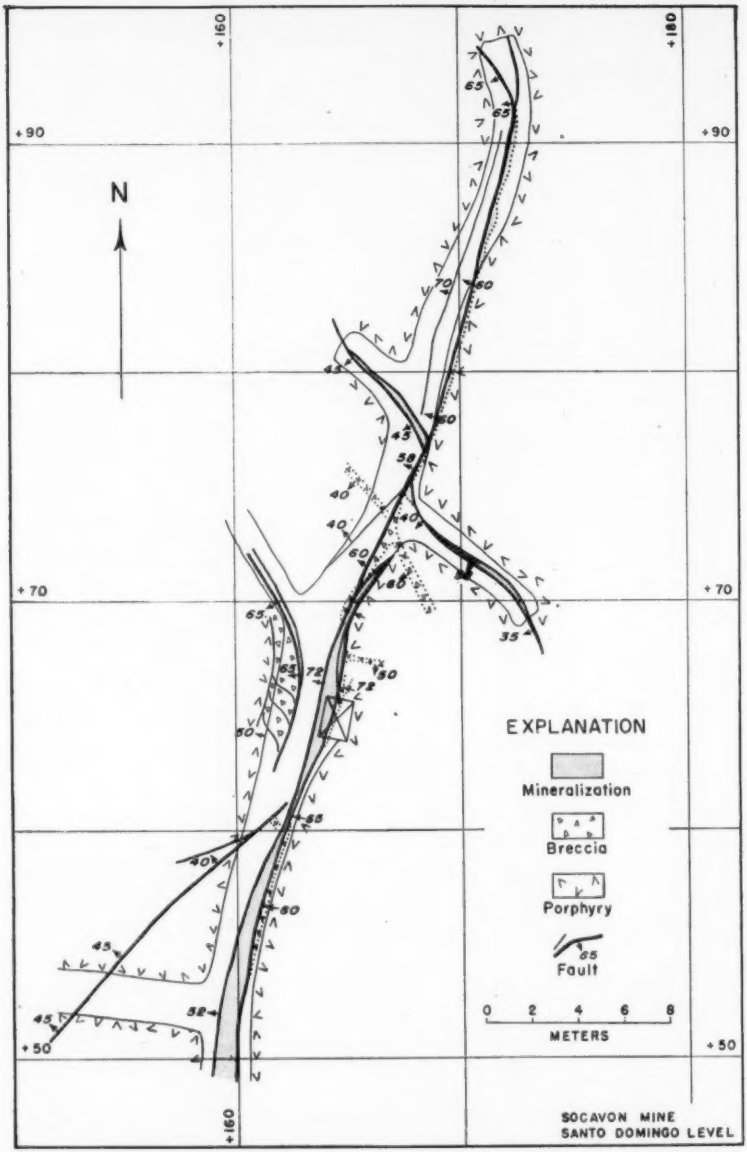

FIG. 29. Map of the Quintanilla vein, Santo Domingo level, Socavón mine, showing the close control exerted by pre-mineral fractures on the distribution of mineralization.

similar hanging-wall fracture on the Grande vein of La Colorada mine extends for 30 m along the − 116 level and 45 m below it.

The striae along the pre-mineral fractures are always nearly parallel to the dip, never departing more than 20°. Irregularities in striae and mullion suggest that in many cases the hanging wall has moved up relative to the footwall. Possibly there has been some normal faulting, but definite proof of this was not found. The exact amount and direction of displacement is not known, for there are no offset intersecting structures; but the movement is believed to be small, because the fractures themselves are relatively short in strike and dip length. Rock contacts are rarely displaced by the movement on the fractures or veins. To cite two outstanding examples where veins crossing contacts are well exposed: the contact between breccia and argillite is not offset by the San José vein where it crosses the rock junction on the −200 level; and the contact between porphyry and argillite cut by the San Luis vein (Fig. 27) likewise shows only slight displacement.

Probably some hinge movement took place along the faults, as indicated by the change in angle and direction of striae on the same fault surface. Also, it is probable that the amount of movement becomes less as the faults curve in strike and dip, and horsetail into weak fractures.

Shingle Veins.—The en échelon and overlapping relations of the veins suggest the "shingle structure" found at Casapalca, Peru, and described by McKinstry and Noble [25] as follows:

> In the porphyry of the Carlos Francisco mine, the veins lie in en échelon or overlapping relation to each other locally termed "shingle structure." Where the hanging wall "shingle" dies out downward, it is usually connected with the footwall vein by a vertical vein which may be wide and rich. In some cases the "shingles" are "reversed"; that is, the footwall vein is the one that dies out, and in this case there is no strong connecting vein.

At Oruro the "shingle structure" is on a much smaller scale than at Casapalca; the "shingles" are closer together and are not connected by a link except in a few places. As at Casapalca, when a break dies out going up the dip of a vein, another one appears in the hanging wall and overlaps the footwall break. In some cases, however, the position is reversed and the en échelon fracture is in the footwall.

Figure 28 A is a map of a part of the Purísima vein where the curving fractures are formed with no complicating factors and illustrates the "shingle" pattern in plan. The fracture in the southeastern part of the map, on being traced northwest, has a uniform strike, but after 25 m, it gradually curves to the north and dies out in a short distance. Where this change takes place, another fracture appears to the left across an en échelon gap; on being traced this is found to have a shape similar to the first break. It should be noted that the stoping along the vein follows the curving fractures very faithfully, but ends where the vein curves to the north.

A more common pattern is that illustrated in another part of the Purísima vein on the same level, shown in Figure 28 B and in section in Figure 28 G.

[25] McKinstry, H. E., and Noble, J. A., The veins of Casapalca, Peru: ECON. GEOL., vol. 27, No. 6, pp. 501–522, 1932.

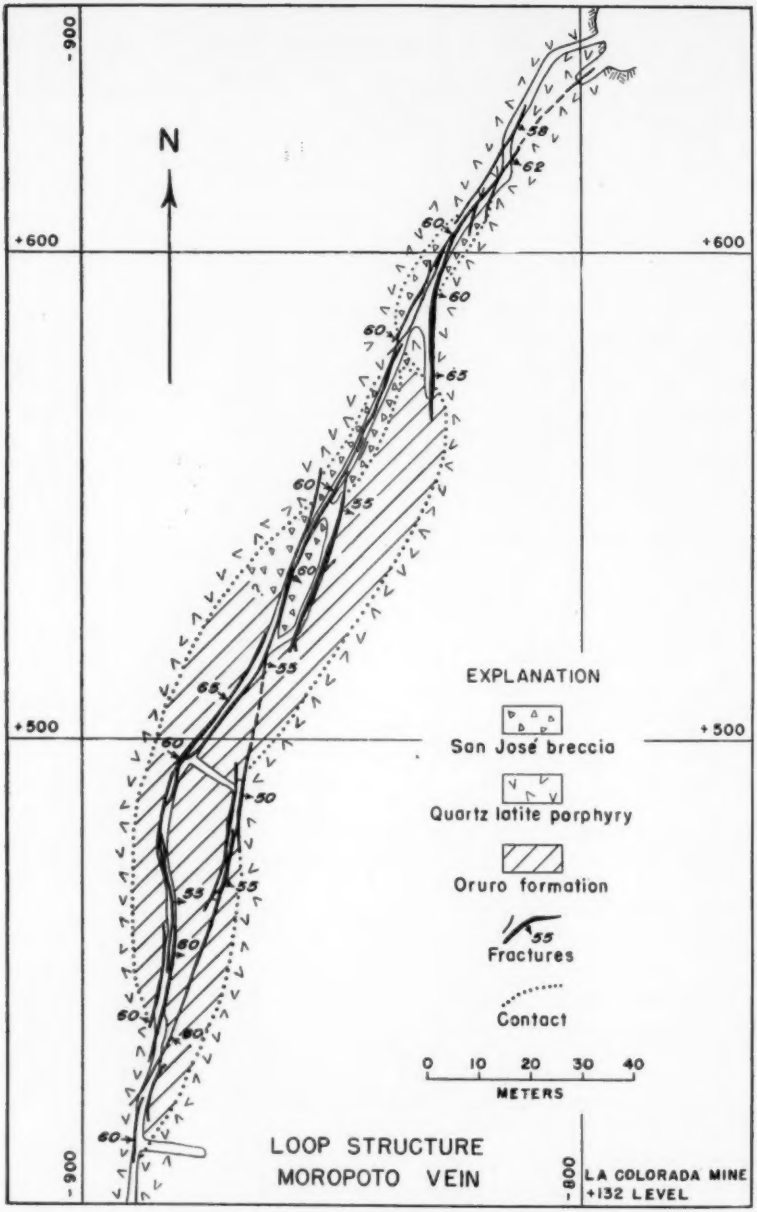

FIG. 30. Loop structure. Map of a part of the Moropoto vein, La Colorada mine, showing a succession of "loops."

There the fractures follow a contact between porphyry and argillite and are a succession of flat-S, reverse S, and arc-shaped cracks. The main fracture followed by the San José vein (Fig. 28 C) is unusually persistent, but where it passes toward the south from breccia into argillite, it curves and splits into a spray of closely spaced cracks. "Horsetail" structure is a fairly common feature associated with the larger fractures, but the relationship to rock contacts shown in Figure 28 C is exceptional.

Sheeted Veins.—In the Itos mine, veins have formed along sheeted zones in the porphyry (Fig. 28 D). The sheeted cracks are closely spaced, straight, and parallel, as in a typically sheeted rock. Careful plotting of dips and strikes of the joints in the Itos porphyry shows that they form a definite system and that the sheeted zones are always parallel to one of the joint directions. In fact, the joints themselves are mineralized in many places. The sheeted fracture zones thus appear to be determined by the joint system where the rock failed along closely spaced cracks parallel to one of the directions. It is interesting to note that sheeted veins are absent in the other porphyry bodies in the Oruro district, although joints are common.

Loop Veins.—A variation of the "shingle structure" is found in a few places where the veins follow a series of branching and reuniting fractures which form one or more flat "loops." The veins, in these cases, enclose a

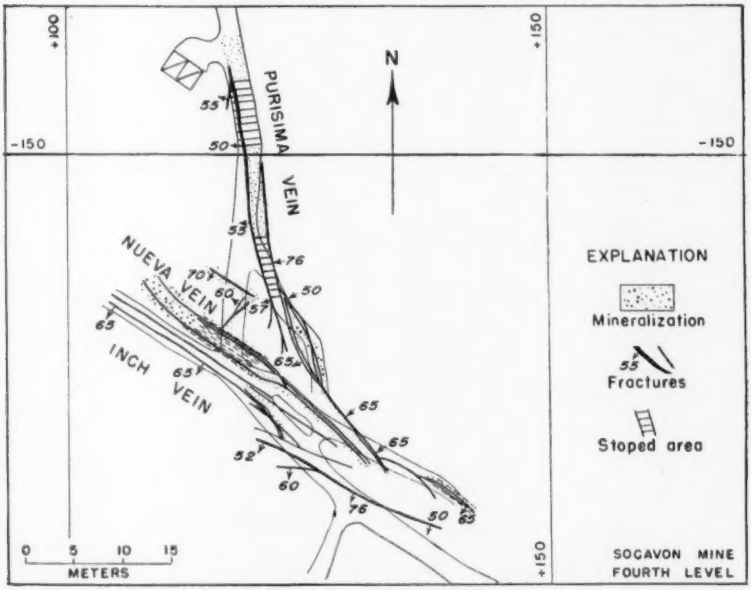

FIG. 31. Map showing behavior of Purísima, Inch, and Nueva veins at an intersection.

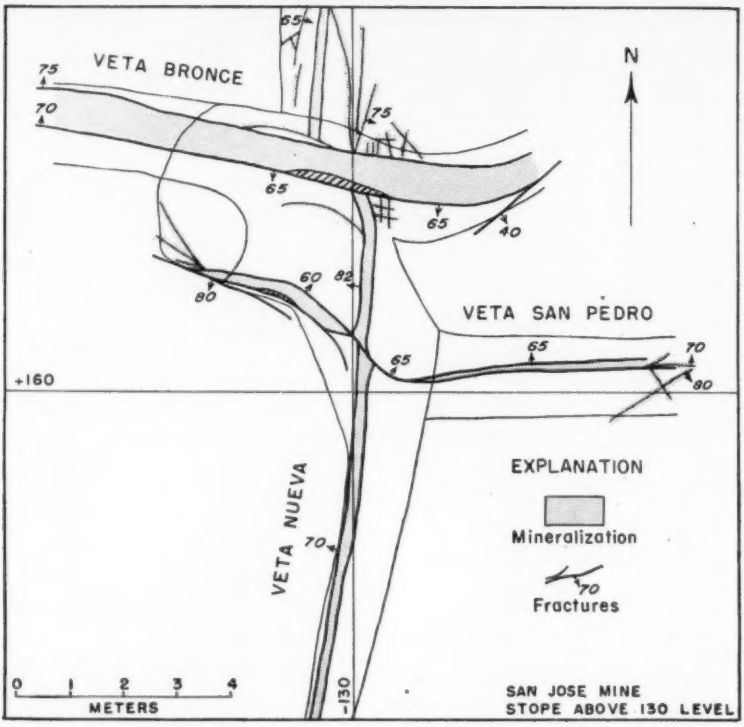

FIG. 32. Intersections of Nueva and San Pedro veins, and Bronce and Nueva veins.

bi-convex lens or ellipsoid-shaped body of country rock which in a sense is a "horse." The Bronce vein has a well-developed "loop" between the –280 and –310 levels. It is illustrated in section in Figure 28 H.

The Moropoto vein of La Colorada mine is, in part, made up of a series of "loops." In several places (Fig. 30), fractures followed by veins have branched from the main line of the vein, continued for some distance, and then curved in strike, and reunited with the main vein. Drifting and stoping have followed both branches of the vein. The "loops" have formed where the fractures follow a narrow septum of argillite caught between the contacts of two bodies of porphyry. Possibly, the long, narrow body of incompetent argillite localized fracturing here, and the curving contact of the massive porphyry influenced rock failure, causing the branching and reuniting fractures to form as a reflection of the contact shape. In depth, the vein departs from the septum because of its flatter dip, and the "loop" structure is no longer present.

Vein Intersections.—Intersections of veins in the Oruro district are remarkably few. The –100 level map (Fig. 23) exhibits four intersections, but only one is between important veins. This is where the Nueva vein crosses the Bronce and San Pedro veins. The –200 level plan of the San José mine (Fig. 25) shows no intersections at all.

The fractures tend to die out where they approach one another, and even major fracture zones of differing strike curve away from one another when nearing junctions. Many veins split along their strike and dip in such places and become arranged en échelon. Figure 31, map of a part of the fourth level of the Socavón mine, shows the characteristic behavior of fractures at intersections. Here, three veins, Purísima, Inch, and Nueva, converge on the level, but the fractures split and die out with no actual crossing or offsetting.

In the small veins, actual crossing of fractures are found, but usually without perceptible offset. In a few places, displacements of a few centimeters up to one or two meters have been observed. Where the Bronce and San Pedro veins cross the Nueva vein in the stope a few meters below the intersection of these veins, the Nueva vein has been offset about one meter (Fig. 32).

The tendency of veins to split going up the dip in such a way that many more are found at the surface than in depth was previously noted. Normally, the places of splitting are also shown as intersections on the generalized maps. They appear as junctions, but when these places are studied in detail, it is found that in most cases no actual intersection exists. The pre-mineral fractures behaved in section as they do in plan; that is, the fractures tend to die out where they approach one another, change in dip when nearing junctions, and result in the en échelon pattern.

In the Itos and La Colorada mines, the opposing dip of veins gives rise to what appear to be intersections on the generalized cross sections. These may be interpreted either as pre-mineral faults with offset of one set of fractures by another set, or as a system formed essentially contemporaneously, with no displaced fractures. The Grande vein on the upper levels follows a relatively flat dipping fault (40°). Several steeply dipping veins are found on the hanging wall and footwall of this flat vein. De Wijs [26] interpreted this structure to mean that the more steeply dipping fractures had been displaced by the flatly dipping fault prior to mineralization. However, attempts to match offset hanging wall and footwall structures were not satisfactory. A more probable explanation is that the fractures above and below the flat fault are not displaced segments, but rather are unrelated except that all of the fractures in the group formed during the general cracking of the region at more or less the same time. Unfortunately, the upper levels on these veins are no longer accessible so it was not possible to study this structure.

The veins in the Itos mine form a system with the northeasterly dipping fractures terminating in depth against the San Luis vein (Fig. 27), which dips in the opposite direction. Other veins appear in the footwall of the San Luis vein. Possibly the fractures followed by the San Luis vein faulted the northeasterly-dipping ones prior to mineralization. If this is true, the hang-

[26] De Wijs, H. J., Private report to Compañia Minera de Oruro.

ing wall veins have displaced segments in the footwall of the San Luis vein. However, it is more probable that most of the cracks of the system formed more or less contemporaneously, as did those of the Grande vein. If this is true, the hanging-wall veins have no displaced segments in the footwall; however, this does not preclude the possibility of veins below the San Luis vein which were formed independently of the hanging-wall structures.

Sequence of Fracturing and Mineralization.

As previously stated, the veins formed in part by replacement and in part by open-space filling along the fracture zones. They usually have one well-defined wall, and in places two walls. Locally a strong fissure marks the center of the vein, and the mineralization grades away into the country rock to an assay limit. The combined processes of open-space filling and replacement have been active in most veins, and it may not be possible to determine which one has been predominant. In many places, open-space filling is indicated by rough banding in the ore and druse-lined vugs. Elsewhere, replacement has been dominant, for residual fragments of wall rock partially replaced are found in the veins. In this case, no well-defined wall is present, and the ore grades off into the country rock to a wavy, indeterminate limit.

The pre-mineral fractures are obliterated in places by replacement, but in general they can be followed with ease. In some cases, particularly in the long, central fractures of the San José vein, the fault is marked by a line of vugs elongated parallel to the strike of the vein. The vugs are lined by quartz and pyrite crystals, and in places are partly filled by later silver minerals. Mineralization has spread into the wall rocks on both sides of the central fault and has partially replaced the rock. The limit of ore here is an assay boundary.

The greater part of the fracturing took place, and the lines of the channels which guided circulating ore solutions were determined prior to the inception of mineralization, but there is abundant evidence that cracking continued throughout the period of growth of the veins. Crude banding in the veins with slivers of altered wall rock suggests that reopening of the veins occurred and that accumulation of ore was by accretion.

Fracturing during the period of mineralization took advantage of the old lines of weakness and caused reopening and cracking of the early veins. This inter-period fracturing does not indicate strong earth movements, but rather minor adjustments, possibly brought on by the surge of ore solutions under high pressure.

Throughout the mines, it is evident that the hypogene mineralization was active in two stages separated by a period of minor fracturing. In the early stage quartz-pyrite-cassiterite veins were formed, and in the later stage silver-bearing sulpho-salts, galena, franckeite, and stannite in distinct veins cut the early mineralization. The silver mineralization was superimposed on the quartz-pyrite-cassiterite veins, and in general the veins of the two stages are coextensive. The minerals of the later stage are found coating the walls and filling vugs in the pyritic ore, disseminated through the early vein minerals

as replacement products, and in places form small, irregular veins cutting across the cassiterite veins (Fig. 33). In several localities, minerals of the sulpho-salt stage are found in well-defined veins, 5 to 15 cm wide, running parallel with the early veins. Usually the later veins follow the center of the pyritic veins, but in places they are on the hanging wall or footwall.

In a few places, the early veins have been offset by fractures now occupied by silver-bearing minerals. The veins shown in Figure 33 are a good example of this point. Here a silver-bearing vein, 2 to 4 cm wide, followed a fracture across a quartz-pyrite-cassiterite vein, 40 to 60 cm wide. The walls of the early vein have been clearly offset several centimeters along the later fracture.

In a few localities, cassiterite-bearing veins are found with no minerals of the second stage, and in other localities veins carrying minerals of the second stage only are found. Some veins are characteristically high in tin and low in silver, whereas others have a high content of silver and are relatively low in tin. The Ramos de la Plata group of veins in the San José mine were apparently rich in silver and low in tin. In a few places, as in the walls of the San Luis vein of the Itos mine, silver-bearing minerals have filled joints in the quartz latite porphyry adjacent to a large vein mined principally for its tin content. In 1937, the walls of this vein were being stoped with success (Fig. 34).

Post-Mineral Fracturing.—No post-mineral faults or fractures of any magnitude of displacement are known in the district. In fact, there are relatively few unmineralized fissures. However, small post-ore faults are found in a few places with displacements of a few centimeters; never over one meter. Slickensided sulphides are found and indicate local readjustments along old lines of weakness.

Summary.—A summary of the more important features of the fracture system and the characteristics of the individual fractures is outlined as follows:

1. The veins occur in four distinct clusters: San José; Itos; La Colorada; Tetilla. These clusters are arranged geographically on the periphery of an imperfect ellipse, and individually, each cluster has characteristics common to the other vein groups as well as features of dissimilarity.
2. Each cluster is made up of a major fracture or a fracture system with numerous associated minor fractures, either as conjugate members, as branching members, or as a combination of various fracture types. Shear and tension breaks can be distinguished in each fracture set or system.
3. The position and attitude of each fracture system has a consistent relationship to the location and attitude of the quartz latite porphyry body with which it is associated. One set tends to parallel the elongation of the porphyry bodies, whereas the other set tends to be arranged at right angles to the porphyry contacts.
4. Most of the veins occur in the intrusive bodies. Although a few veins are found in the Oruro formation, most of those passing from porphyry into argillite or slate die out in a short distance.
5. The veins are more regular on the lower levels of the mines and more complicated near the surface. The veins tend to branch upward due to the fact that fracturing was more complex near the surface than at depth. There-

fore, many more veins are found on the surface than on the lower mine levels. Probably the underlying reason for a difference in fracturing is that there is much more brittle porphyry near the surface than at depth.

6. The dip of several of the major fracture zones, such as the San Luis, tends to steepen in depth, whereas others, such as the Purísima, Bronce, and Grande veins, have a fairly uniform dip or tend to flatten somewhat, where followed downward.

7. The pre-mineral fractures are nearly all of the same general type. They are a series of curving, flat S, reverse S, and arc-shaped breaks, arranged either en échelon or overlapping, which as a set form a "shingle structure." "Sheeted" and "loop" veins are common and may be regarded as local variations of the normal type.

8. The stronger, more persistent fractures are well defined with smooth, polished walls, which commonly have striae, mullion, and gouge along them. The striae are nearly always parallel to the dip, never departing more than 20°. They indicate in places that several movements have occurred along the pre-mineral fractures and that in a few places hinge movements have taken place. These fractures are interpreted as shear breaks; where they curve from the average trend and die out, they are interpreted as tension breaks.

9. The direction of movement along the fracture is usually obscure. There is some suggestion that the hanging wall has moved up relative to the footwall, but some of the major fracture groups suggest that in certain cases the hanging wall has moved down. Offset rock contacts have been found in only a few places. In general, the movement along the individual fracture is believed to have been slight.

10. The fractures are generally more persistent down the dip than they are horizontally. This has had an important effect on the size and shape of ore shoots.

11. The larger ore shoots occur where the fractures are strongest and where they are parallel to the general trend of the fracture set. Where the individual fractures die out or where they curve from the average trend, the ore shoots die out or break up into horsetail structures.

12. Brecciation of wall rocks took place along most of the veins near the surface, but in depth rock failure was confined to regular, uncomplicated fractures with striae and slickensides,[27] and without breccia.

13. Individual fractures tend to die out at intersections. Important displacements of one fracture by another are not found, and even minor displacements are rare.

14. The greater part of fracturing took place, and the fractures which provide permeable channels for circulating ore solutions were determined, prior to the inception of mineralization. There is abundant evidence, however, that cracking continued throughout the period of growth of the veins and that intermineralization fracturing took advantage of old lines of weakness and caused reopening and cracking of the early veins.

15. Post-ore faults have not been found in the district, except for very minor adjustments along small faults which have been found in only a few places.

[27] This generalization was pointed out by Campbell, and is believed to be correct. See Campbell, D. F., op. cit., p. 103.

Origin of the Fracture System.

The origin of the fracture system may be considered logically in two steps. The first and most fundamental step is an analysis of the stresses that caused rock failure. An understanding of the magnitude and direction of the forces that caused the fracturing can be reached only by a detailed study of the fracture types present—whether they are shear or tension breaks, or both; what their position is in space with respect to one another; what the direction of movement is along them; what their relation is to the associated rock bodies; and what other peculiarities may be present.

Once acceptable conclusions have been reached concerning the stress-strain relations, the second step is an appraisal of the nature of the forces that resulted in failure. Without an understanding of the behavior of rocks under stress and of stress orientation preceding and during failure, little progress is likely to be achieved in evaluating the causal forces themselves—whether they were of a regional dynamic character or were localized in nature and were caused by withdrawal of support from beneath, upward thrust from depth, or other unknown forces.

Stress Analysis.—Although the fractures of the Oruro district form a fairly consistent system with many characteristics in common, it is apparent from even a casual perusal of the maps and sections that as a group they do not resemble the ideal or theoretical fracture pattern of two sets of conjugate shears with a set of tension breaks bisecting the angle between them.[28] The ideal fracture pattern, of course, is rarely found, even in fairly homogeneous rocks, yet it is roughly approximated in many districts.

Considering the district as a whole, it is obvious from the multiplicity of fracture attitudes that a single tension direction and two well-defined shear directions cannot be established for Oruro. Moreover, the nature of the fractures themselves indicates that two definite shear directions and a definite tension direction do not exist here. Therefore, the orientation of a strain ellipsoid, or even strain couples, that would fit the attitude of known fractures for the district as a whole is manifestly impossible.

A study of the fractures in the individual vein clusters is somewhat more fruitful, for grouping of the veins into distinctive clusters seems to have more significance than strike groupings; furthermore, the fractures in the individual clusters appear to have greater resemblance to those of the ideal fracture pattern. This is particularly true of the San Luis cluster, where a conjugate system is developed with veins having parallel strike and opposite dip. However, veins having two totally different dips and strikes are present, neither of which can be considered to indicate a tensional direction. The veins of the cluster, therefore, although closely related and unusually regular, do not strictly conform to the ideal pattern.

In general, it may be concluded from a study of the Oruro fracture system that it is not possible here to arrive at a satisfactory conclusion concerning stress orientation during rock failure. This does not mean that a theoretical

[28] See McKinstry, H. E., Structural control of ore deposition in fissure veins: Am. Inst. Min. Met. Eng. Tech. Pub. No. 1267, 1941.

analysis of the stress-strain relations is valueless. On the contrary, the fact that it does not conform to the ideal pattern is believed to have considerable significance and has some bearing on the origin of the ore deposit itself.

Two reasons are at once apparent for the divergence of the fracture pattern from the ideal—the nonhomogeneous character of the wall rocks and the complexity of the stress history.[29] The stresses which produced rock failure in the Oruro district acted on an assemblage of nonhomogeneous rocks; that is, on relatively brittle porphyry enclosed in incompetent argillite with irregular masses of breccia of varying competency scattered throughout the district. The strength of the rocks varied in different directions, and fractures developed along lines of weakness, such as contacts between argillite and poryhyry, and along joints in the prophyry.

Stresses applied to such a nonhomogeneous mass, whatever their nature or origin, or direction of application, would be transmitted in several directions, depending on the physical properties of the rocks, and would result in nonuniform stress. Under these conditions, failure would take place where stresses reached a maximum exceeding the ultimate strength of the rocks, and fractures would tend to develop with several directions of strike and dip. Local variations in strength of the rocks and pre-existing lines of weakness, such as joints or contacts, play an important part in the localizing of later stresses, and determine where later failure and openings take place. Undoubtedly, these conditions were in a large measure responsible for the development of the Oruro fractures.

A second reason for the departure of the fracture pattern from the ideal is that the fractures of the district did not form simultaneously. Although they developed in a single period of stress, somewhat sustained, and the greater part of rock failure preceded the onset of mineralization, deformation in a mild way continued throughout the mineralization period with fracturing and reopening of veins along old lines of weakness. Probably some reorientation of stress occurred with the formation of new fractures, unrelated to the earlier ones, and further complicated the fracture pattern.

The general short, curving character of the fractures and their failure to offset rock contacts indicate a general cracking of the region rather than intense deformation which would have formed major through-going fissures and fault zones. The fact that the fractures are flat-S-shaped and curving, with well-defined fault walls, suggests that they were originally tension breaks along which slight movement took place at a later time with continued application of stress after the initial cracking. It seems reasonable to conclude that the magnitude of the stress was relatively small, just enough to cause definite lines of fracture and cracking, but not enough to rupture the entire rock mass and convert the lines of fracture into through-going, persistent breaks with appreciable offsets. The continuation of the stresses and the repeated fracturing during the mineralization period created and maintained permeable channelways which appear to have been more decisive in the formation of the fracture pattern than the magnitude of stress at any given time.

[29] See McKinstry, H. E., Use of the fracture pattern in the search for orebodies: Australian and New Zealand Assoc. Adv. Sci. Rept., Melbourne Meeting, January 1935.

Probably the shape and distribution of the brittle porphyry was the most important factor in failure, determining the character and localization of the cracking. The occurrence of veins and fractures in individual clusters undoubtedly was determined by the position of the brittle porphyry bodies and the lines of weakness along the contacts of the porphyry with argillite or breccia.

The general aspect of the fractures, branching and increasing in complexity toward the surface, clearly indicates that they formed at shallow depths. The "shingle" structure with "sheeted" zones, "loops" and minor links is in accord with this concept. Structurally, the veins are comparable with those in districts such as Virginia City, Nevada, and the San Juan Mountains, Colorado, which are believed to have been formed near the surface. The structural features of deep veins are lacking.

Causes of Fracturing.—At the present time, one can only speculate on the nature of the causative stress which produced the fracture system. Regional stresses; stresses set up during the emplacement and crystallization of the porphyry bodies; withdrawal of support from beneath with consequent slumping; upthrust forces from depth, all must be considered as possibilities. However, although they cannot be ruled out completely, for various reasons, several of the possible causes seem improbable.

In many mining districts, regional stresses are commonly invoked to explain fracture systems which controlled and localized ore deposits. However, the characteristics of the Oruro system are such that regional compressive forces do not seem to have been the causative agent. The fracture pattern is not a part of a regional fracture system; the fractures are arranged in clusters and are not persistent for long distances and do not extend far from the local porphyry bodies. A careful examination of the surface away from the mine, where the igneous rocks are well exposed, disclosed that a series of joints is present; but a regional pattern comparable to the fracture system found in the vicinity of the mines does not exist. Moreover, the Oruro pattern does not resemble that in districts such as Butte, Grass Valley, and Llallagua, where regional compressive forces have been invoked to account for the fracturing.

The orientation of the fractures at Oruro does not correspond to the attitude of "stretching" faults, "marginal" thrusts or "marginal" "gash" fractures, and other structures described by Cloos and Balk,[30] which are believed to be caused by stresses set up during the emplacement and crystallization of granite bodies. Moreover, the Oruro fracture system was undoubtedly superimposed on both the igneous and sedimentary rocks after the intrusion had completely crystallized. The forces that caused deformation, therefore, acted on solid rocks sometime after emplacement and solidification.

Campbell [31] reviewed the subject of the origin of the fractures in some detail. He recognized the close relationship between the porphyry bodies and the fractures, and suggested that the larger porphyry bodies, such as those that make up Cerros San Felipe and Viscachani, were areas of uplift due to igneous intrusion, whereas the areas between them, occupied by the

[30] Balk, Robert, Structural behavior of igneous rocks: Geol. Soc. America Memoir no. 5, July 1937.

[31] Campbell, Donald F., op. cit.

porphyry bodies of Cerros Todos Santos and La Colorada, were areas that collapsed. Thus Campbell interpreted the fractures of the Purísima and Bronce system as reverse faults which dip toward the area of uplift. The fractures of the San José, Grande, Moropoto and San Luis vein systems, on the other hand, were interpreted as normal faults around the area that collapsed. The cause of the uplift, according to Campbell, was upthrust of the intruding magma or its vapor pressure.

The mechanism that Campbell suggests provides localized stresses which appear to be necessary to account for the fracturing. However, that uplift of certain areas accompanied by subsidence of others occurred is unconvincing and without the support of field evidence. Structural elements indicative of uplift of the San Felipe and Viscachani bodies are lacking. Moreover, subsidence of the central area would necessitate at least observable movement along the fractures of the San José, San Luis, and other systems. Although slight offsetting took place along some of the veins, it was not sufficient to result in detectable subsidence. For example, Campbell's [32] cross section of the San Luis vein shows no displacement of the contact between shale and "rhyolite porphyry" where it is crossed by the main San Luis fractures.

Although it is probable that the stresses responsible for the fracturing in each cluster resulted in slight reverse-fault movement in certain instances and normal faulting in others, the magnitude of the stresses was sufficient only to cause a general cracking along fairly definite lines of weakness, but not strong enough to cause appreciable movements or offsets along the breaks. With such incipient faults it is difficult to determine which areas would have been uplifted, and which areas would have subsided.

In considering the origin of fractures and ore deposits controlled by fracturing, two sets of conditions can be conceived. The first condition is that in which fractures and fissures are believed to have existed in the rocks sometime prior to mineralization, having been caused by stresses unrelated to mineralization. When the ore solutions flowed in, they took advantage of these openings and had little or no influence in altering them. Undoubtedly, this condition has existed in many ore deposits.

The second condition is that in which fracturing and mineralization are believed to have been closely related phenomena in time and space and to have been caused by essentially the same processes. Previously existing lines of weakness would have had considerable influence on the position and attitude of the fractures; but the specific breaks and openings occupied by vein minerals would have been caused by stresses set up immediately before and during mineralization, the two phenomena having a common origin—probably magmatic activity in depth.

Since Spurr [33] first pointed out that areas of intense mineralization are in many places areas of intense faulting, and suggested that there is probably a genetic relation between the two, evidence has accumulated to indicate that igneous intrusion, fracturing and faulting, mineralization, post-ore faulting, and post-ore diking are closely associated events and that they have a closely connected origin.

[32] Campbell, Donald F., op. cit., Figure 6.

[33] Spurr, J. E., The relation of ore deposition to faulting: Econ. Geol., vol. 11, pp. 601–622, 1916.

This general sequence is duplicated in many mining districts throughout the world. The closely related sequence of events which occurred at Oruro —intrusion of porphyry bodies, pre-ore fracturing, mineralization, and intermineralization fracturing and faulting—is undoubtedly an example of this phenomenon. However, the process apparently ceased with the end of hypogene mineralization, for post-ore faulting is negligible, and there are no post-ore dikes.

In those cases where an intimate relationship is believed to have existed between fracturing and mineralization, two mechanisms, which may be applicable to Oruro, have been proposed, and applied to specific districts, to explain the fracturing: (1) the explosive force of vapor pressure built up during the crystallization of magma at depth; and (2) the subsidence of overlying rocks due to contraction of crystallizing magma at depth, or withdrawal of magma.

(1) The first of these processes has been reviewed in considerable detail by W. H. Emmons.[34] In general, Emmons suggests that if vapors are expelled in the process of crystallization, according to the Morey principle of resurgent boiling, then a granite batholith, in crystallizing, would probably build up enough pressure to lift two or three miles of granite. Therefore, to quote Emmons directly, ". . . vapor collecting near the tops of cupolas or batholiths, is believed to exert sufficient pressure to fracture the hoods and roofs of batholiths above the cupolas."

(2) The second mechanism proposed to explain fracture systems closely related in origin to mineralization is the subsidence of overlying rocks due to contraction of crystallizing magma, or withdrawal of magma; this would seem to be an ideal way of producing tensional cracks in localized areas of the type found at Oruro. This subject has been discussed by Hulin,[35] who attributes formation of pre-ore fractures and intermineralization fracturing to volume decrease of crystallizing magma in depth with resultant shrinkage and collapse of the overlying rock body and to subsequent thermal contraction of the rock body.

Without entering into a detailed consideration of the relative merits of these two mechanisms, because of their theoretical nature, it may be said that in favor of either mechanism is the fact that the timing would be about right to develop fractures when receptacles were necessary; and either one conceivably might provide the localized stresses necessary to cause the fracture clusters.

Conclusions.—Although it is manifestly impossible to arrive at satisfactory conclusions concerning the nature of the causative stresses which resulted in fracturing, and it is apparent that none of the hypotheses discussed provides an entirely satisfactory explanation of the structural features, certain conclusions seem justified and may be summarized as follows:

1. Fracturing occurred in local areas and took advantage of previously existing lines of weakness. It was concentrated in the brittle porphyry and along its con-

[34] Emmons, W. H., On the origin of certain systems of ore-bearing fractures: Am. Inst. Min. Met. Eng. Trans., vol. 115, pp. 9–35, 1935.

[35] Hulin, C. D., Factors in the localization of mineralized districts: Am. Inst. Met. Eng. Tech. Pub. No. 1762, New York, 1945.

tacts with argillite or breccia, and resulted in a general cracking of the area along fairly definite lines of weakness without forming major, through-going breaks or faults. The fracturing was not intense enough to cause appreciable movement or offsets along the breaks.

2. The fracture patterns and the accompanying tensional openings are indicative of expansion rather than contraction or shearing.

3. Many details of the fracture patterns and of individual fractures indicate that failure took place in a near-surface environment under light load and at shallow depth. The structural features of failure at depth under high pressure are entirely lacking.

4. For various reasons, regional orogenic forces, stresses set up during the emplacement of the exposed igneous rocks, and major uplift and subsidence are ruled out as possible causes of failure.

5. The fractures were caused by differential vertical stresses set up in local areas during the period of igneous intrusion, formation of the San José breccia, fracturing and ore deposition.

6. Fracturing at Oruro was closely related to the process of mineralization, both in time and place. The stress that caused pre-mineral fracturing continued in a mild way throughout the mineralizing period, but ceased with the end of hypogene mineralization.

7. The fracturing can be attributed either to upward pressure from depth which caused slight, local doming with resultant tension fractures, or to withdrawal of support from beneath accompanied by slight subsidence with the development of incipient synthetic and antithetic faults. The view favored by the author invokes both upthrust and subsidence.

8. The distribution and the nature of the fracturing are best explained by relatively feeble jolting from below. The jolting was sufficient to lift the igneous rock bodies slightly and to let them slump back somewhat, thereby causing fracturing. The force was not sufficient, however, to cause fragmentation and churning of rock fragments, as did the explosive force that caused the San José breccia, nor was it strong enough to cause appreciable movement on the fracture planes. The recoil from upthrust with mild subsidence under the control of gravity would account for striations parallel to the direction of dip and for the slight reverse faulting.

9. The precise origin of the jolting is not known, but probably it was the same magmatic activity at depth which (a) gave rise to the quartz latite porphyry intrusions and extrusions; (b) was the origin of the explosive force which formed the San José breccia; and (c) was the source of the ore solutions.

The jolting may have been the final manifestation of the explosive activity which accounted for the San José breccia. Conceivably, vapor pressure, built up during the crystallization of igneous rock at depth, was the cause of the early explosive activity and the later more feeble jolting that produced the vein fractures. It may also have been the propelling mechanism that forced in the ore solutions.

PRODUCTION OF THE ORURO DISTRICT.

The ore deposits at Oruro contain a variety of metals, including tin, silver, copper, lead, antimony and arsenic, but only silver and tin have been important from the point of view of production. A small amount of copper and lead has been produced in the past, and during World War II considerable antimony production was reported.

By piecing together scattered data available in the literature and utilizing the records of Compañia Minera de Oruro since 1920, it may be computed that the total silver production from 1595 to 1944 was roughly 8,429,000 kilograms or approximately 270,990,000 ounces. As data are missing for a period of many years, it seems possible from the fragmentary records that the deposits yielded at least 275,000,000 ounces of silver.

A conservative estimate of Oruro's total tin production is 45,000 metric tons. Taking into consideration the lack of data for many years and the fact that tin recovery from the ore averages less than 60 percent, it seems that the actual volume of tin concentrated in the Oruro deposits must have been considerably more than the above figure indicates.

During the period from 1930 to 1944 Oruro accounted for 3.8 percent of Bolivia's tin production and 13.5 percent of its silver output. From 1940 to 1944, an average of 62,365 metric tons of ore after handpicking were shipped each year from the Oruro mines to the Machacamarca mill. This ore averaged 3.49 percent tin and 0.284 kilograms (9.13 oz.) of silver per ton.

Types of Ore.—Three classes, or types, of ore, depending upon mineralogy and occurrence, are found in the Oruro district, and are mined and shipped. These are the (a) "pacos" ore, (b) calcination or mixed sulphide-oxide ore, and (c) flotation ore. Each type, as the name suggests, requires a different treatment method.

(a) Pacos Ore.—This is made up of cassiterite, quartz and chalcedony, and hydrous iron oxide, limonite and jarosite, and is obtained from the oxidized zone. Although spectacularly high grade silver ore was found in the zone of oxidation during the early days, it appears to be exhaused and the pacos ore now contains no silver. After handpicking, the pacos ore is further concentrated by gravity methods, using jigs and tables, and then by magnetic separators. In the period from 1940 to 1944, an average of 28,480 metric tons of this type of ore was shipped each year, with an average tin content of 3.54 percent.

(b) Calcination Ore.—The calcination or mixed sulphide ore, is composed of cassiterite, pyrite, quartz, and silver-bearing sulpho-salt minerals, such as tetrahedrite, andorite, bournonite, jamesonite, and zinkenite. This ore constitutes the bulk of hypogene mineralization and is obtained from immediately below the zone of oxidation. It is treated for both tin and silver by roasting with chlorides and by magnetic separators. From 1940 to 1944, inclusive, an average of 29,785 tons of sulphide ore was shipped yearly to the mill and had an average content of 3.68 percent tin and 0.48 kilograms (15.4 oz troy) of silver. During this period, about 51 percent of the newly mined material was classed as calcination ore and 49 percent as pacos ore.

(c) Flotation Ore.—This ore is made up of complex silver- and tin-bearing sulpho-salts and stannates, such as the rare minerals, stannite and franckeite, and is obtained from the deeper mine levels, below the − 200 level, on a few veins, particularly Veta Grande. Because most of the tin in these ores is contained in stannite and franckeite, which are known as "soluble" tin ores and from which tin cannot be recovered profitably by present metallurgical methods, mining of this ore type was discontinued in 1940.

Several intermediate and transitional types of ore occur at Oruro; among these are "pacopirita," a mixed pacos-sulphide ore, and "pyritic-tin" ore, but these are not clearly defined, and as far as mining and treatment methods are concerned, they are classed as calcination ores.

To be continued in next number.

HEAVY METALS IN ALTERED ROCK OVER BLIND ORE BODIES, EAST TINTIC DISTRICT, UTAH.[1]

T. S. LOVERING, V. P. SOKOLOFF, AND H. T. MORRIS.

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ABSTRACT.

Standard chemical tests and spectroscopic analyses of altered Tertiary lavas that occur above blind ore bodies in the East Tintic district, Utah, have failed to show any evidence of the mineralization in the underlying dolomites. A new technique involving dithizone was used in the field to test ammonium acetate extracts of crushed samples of the lava for soluble heavy metals, with significant results. Concentrations of heavy metals, believed to be chiefly zinc, with some lead and rarely copper (?), were found in pyritized rhyolite above and up-rake from known blind ore bodies, and were lacking in similarly altered rhyolite underlain by barren rocks. An incompletely prospected area of pyritic alteration shows a definite pattern of positive tests and seems worthy of further exploration. The theory and practice of the dithizone method as used in the field is described briefly.

INTRODUCTION.

BLIND ore bodies are a continuing challenge to the mining geologist. Delineation of structure, study of alteration zones, chemical analyses, assays, and spectrographic work on essentially barren outcrops have been helpful in certain places. Any additional method, however, offering promise of improving the chances of locating blind ore shoots merits attention. A new geochemical technique, developed in areas of hydrothermally altered rock in the East Tintic district in 1947, is described in the present report.

The study would have been impossible without the cooperation of the mining companies in the district. It is rare to find such wholehearted and

[1] Published by permission of the Director, U. S. Geological Survey.

generous assistance as that given by the officials and employees of the Newmont Exploration Company, the Chief Consolidated Mining Company, and the Tintic Standard Mining Company, whether sampler or superintendent. We especially wish to express our appreciation of the help given us by Mr. George Murray, Mr. Cecil Fitch, Mr. J. W. Wade, Mr. Fred Hanson and Mr. Earl Hanson, who did much to make this study possible.

In the East Tintic district the Oligocene (?) Packard rhyolite (quartz latite with some tuff and agglomerate) lies unconformably on strongly folded, faulted, and deeply dissected Paleozoic rocks, consisting of 5,500 feet of dominantly carbonate sediments above a thick basement of unfossiliferous quartzite. The volcanic series and the Paleozoic rocks are cut by intrusive quartz monzonite, latite, and monzonite porphyries, and by "pebble dikes"—dikelike masses chiefly made up of subangular or rounded fragments of the quartzite basement. Hydrothermal alteration has affected all these rocks locally; but ore deposits, though later than the intrusives, have been found only in the rocks below the volcanic series. Most of the output of the district has been from lead-silver-zinc replacement bodies, but a substantial production must be credited to veins of pyritic copper-gold ore and gold-silver tellurides. The veins are almost restricted to fissures that have one or both walls in the basement quartzite.

Nearly all the replacement ores have a casing of pyritic jasperoid which in turn is surrounded by an outer envelope of hydrothermal dolomite, with a narrow transition zone between the two, marked by an argillic (clay mineral) alteration. The solutions that caused these major types of alteration products rose along the available conduits and altered the extrusives and intrusives above the Paleozoic sediments. Many types of alteration products have been recognized and mapped, (6) [2] and those types most closely related to ore deposition can now be pointed out with some confidence, thus greatly restricting the target area. A late-stage pyritic alteration of the lava which directly overlies some of the ore bodies is apparently contemporaneous with the period of jasperoid formation; the chances are excellent that replacement ore is present somewhere beneath many of the areas of late-stage pyritic alteration, unless the lava rests directly on quartzite with no intervening section of limestone or dolomite.

The surface projection of a blind ore shoot commonly covers less than ten percent of the pyritic halo in the lava, and some of these late-stage pyritic-alteration areas are not associated with ore.

A preliminary geochemical study of fresh lava and of several types of altered lava above and remote from ore was undertaken in 1943. Over a hundred assays for gold and silver and many analyses for lead, zinc, and copper in selected test areas gave negative results. The metals, if present, were in such minute quantities as to show not even a trace in carefully assayed samples from outcrops directly over, or up-rake, from known blind ore bodies whose tops were 500 to 700 feet below the surface. Spectrographic studies were then undertaken; analyses of fresh and altered rock showed nearly identical amounts of the various heavy metals. The fresh Packard

[2] Numbers in parentheses refer to Bibliography at end of paper.

rhyolite contained about .004 percent Pb and .01 percent Zn; altered rocks above ore shoots showed .004 percent Pb and .00 percent Zn; and similar results were obtained in altered lava distant from ore. Only ten samples were tested, but the results discouraged the hope that spectrographic analyses would be more fruitful than the methods used in assay laboratories.

The abrupt absence of silver, gold, lead, zinc, and copper above blind ore in amounts determinable by standard analytical methods suggests that if any ore minerals migrated into the altered rocks overlying the ore bodies, the amount present would be of the order of magnitude of that found in the fresh rock, or even less. As shown in Figs. 1, 2, 3, and 4, evidence of introduced ore in these minute quantities was found.

The disparity in concentration of lead and zinc in the ore and that in the barren altered rock overlying the blind shoots is tremendous. It may have resulted from liquid-phase transfer of the metals in the ore shoot and vapor-phase transfer above it. This explanation agrees with the conclusion reached independently (6)[2] that the conversion of the indigenous magnetite of the lava to pyrite in the late pyritic stage, without other chemical addition or subtraction, was caused by H_2S in a vapor phase. It is also possible that barren post-ore liquid solutions rising through the nearly insoluble ore dissolved minute quantities of lead and zinc, transported them upward into the lava blanket, and there exchanged them for iron in the disseminated pyrite.

Experimental work conducted by the authors has shown that the 40 ppm of lead and 100 ppm of zinc present in the lattice of silicate minerals is scarcely detectable in ammonium acetate extracts of one gram of fresh lava. A small fraction of this amount of lead or zinc, if present as sulfide, sulfate, or carbonate, could be easily detected. Thus the chemical method used does not give the total heavy-metal content as does the spectrograph, but rather tells the content of heavy metal present in forms comparable to those found in the ore. Where the term "detectable amounts" of heavy metals is used in this report it refers to the ammonium acetate soluble portion present, not to the content detectable spectrographically or after fusion.

A geochemical reconnaissance was conducted by the authors in 1947 in the field to ascertain, if possible, the relationship between detectable amounts of heavy metals in pyritized rhyolite outcrops in areas of known mineralization. Parallel studies were conducted also in a comparable area of pyritic alteration known to be essentially unmetallized and in an area unexplored and undeveloped economically, where mineralization below pyritically altered rhyolite appeared probable, for geologic reasons. Simple orientation studies at the beginning of the project provided a background for the present report.

Fractionation—that is, testing not for the total but for a certain fraction of the total—proved to be of considerable value in reconnaissance in the Tintic district. Reliance on the "total" concentrations of metals as a guide in geochemical reconnaissance (12, 13) may be conducive to positive correlations in relatively simple kinds of environment. The Tintic work, however, appears to indicate that such total methods as spectrographic and fusion analyses may be less useful in prospecting under certain conditions than techniques that fractionate the heavy metals according to the minerals containing them.

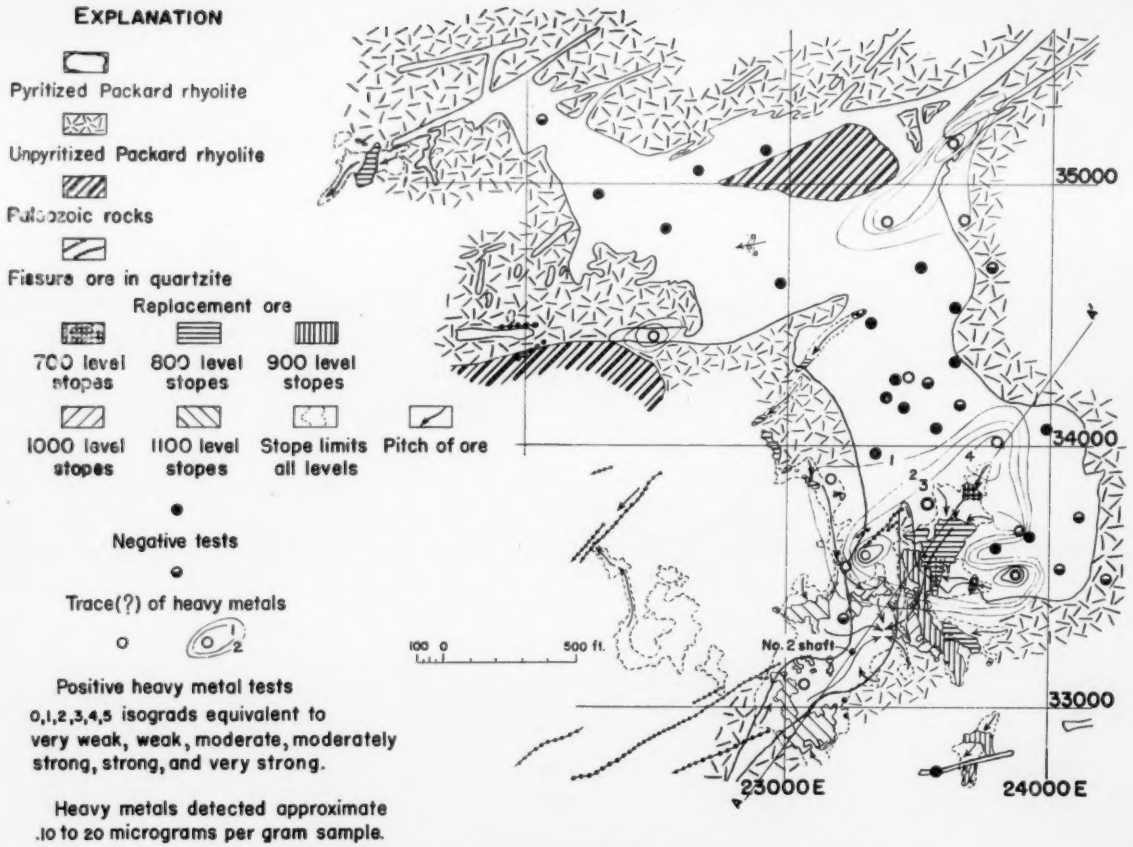

FIG. 1. Geochemical sample map of the Tintic Standard alteration area.

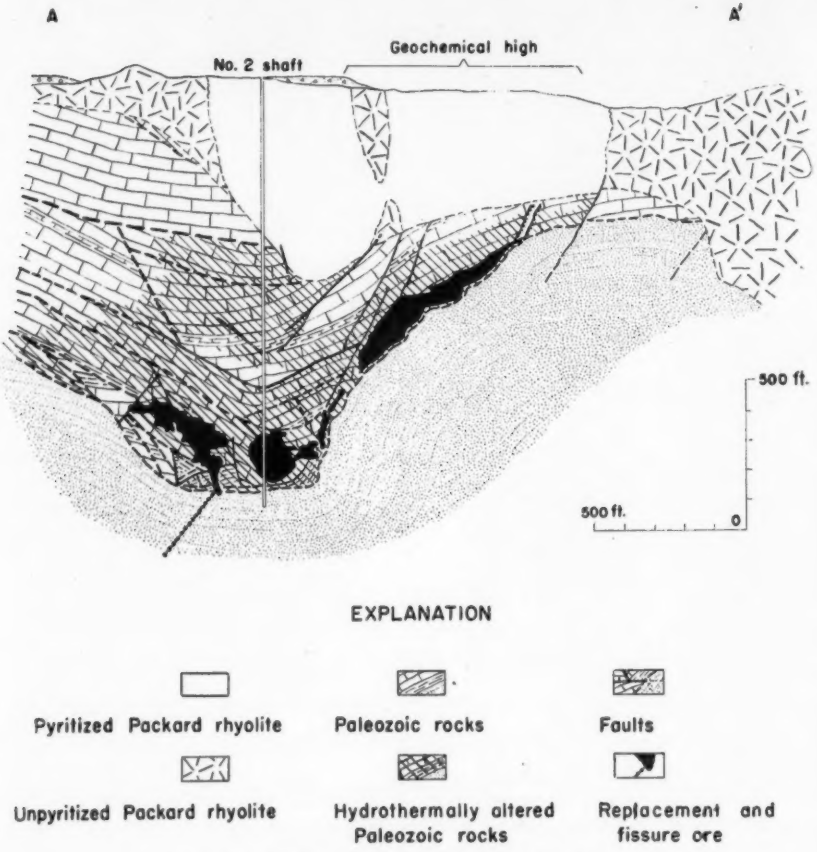

FIG. 2. Vertical section along line A–A′, Fig. 1.

Traces of zinc and lead in the fresh rock in all probability contemporaneous with the formation of the rock itself, are believed due to the ordinary kind of dispersion of the metals in the earth's crust. These traces probably are found in the crystal lattice of certain minerals where, by virtue of their position, they are poorly accessible to the action of the solvent. Traces of zinc and lead in the altered rock, if of a hydrothermal origin, may be related genetically to the deposition of ores at lower depths. These traces probably are associated with minerals other than those containing the syngenetic zinc and lead, as, for example, hydrothermal pyrite and zinciferous beidellite. Here they are both accessible and soluble, under conditions of the test.

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DETERMINATIONS OF HEAVY METALS.

Reagents.—A relatively nonspecific but a highly sensitive reagent, diphenyl thiocarbazone or dithizone, to use its trivial name, was used to ascertain absence or presence of heavy metals in ammonium acetate extracts of crushed rock. The reaction resulting in the formation of colored dithizonates under certain conditions is well known. Certain theories of this reaction and its sensitivity are discussed in Sandell's monograph (10). Dithizone has been employed in the field by a number of investigators (12, 14) in the examination of waters, soils, and fused mineral materials; but it was advantageous in the East Tintic study to use somewhat novel methods both in the preparation of samples and in interpretation of results. A separate paper (15) contains an appraisal of the method and a summary of the precautions necessary to insure uncontaminated reagents and water.

Dithizone is a violet-black, solid, organic dye. It is readily soluble in various organic solvents such as carbon tetrachloride and chloroform, to which a small amount of the dye imparts a green color; it is almost insoluble in acid or neutral aqueous solutions, but reacts with alkaline solutions to form a water-soluble, yellowish alkali dithizonate (10, p. 73). Many heavy metals react with dithizone to form strongly colored compounds, chiefly violet, red, orange, and yellow. Most of the metal dithizonates are more soluble in carbon tetrachloride (and other organic solvents) than in aqueous solutions, whether alkaline or not, differing in this respect from the alkali dithizonates. Thus in a 2-phase solution consisting of carbon tetrachloride and dilute ammonia (pH 9+), essentially all the dithizone combined with a heavy metal remains in the carbon tetrachloride phase, and the remaining dithizone enters the aqueous solution. In the absence of heavy metal the carbon tetrachloride phase, at a pH of 9+, is colorless in the dilute ammonia; thus the presence of very small amounts of colored metal dithizonates is readily recognized because of the faint color imparted to the carbon tetrachloride; the same color might be completely masked by the strong green of the excess dye at a pH less than 8. In addition to the increased sensitivity due to this "color buffer" action in the alkaline solution, the completeness of reaction for many metals decreases sharply with lowering of pH at some point between 7 and 2. Copper reacts well with dithizone at a pH of 2, or even less if the mixture is shaken for several minutes; but in solutions of this acidity neither lead nor zinc react with dithizone, and as a consequence they remain in the aqueous phase, and are most completely extracted in slightly alkaline solutions.

Although 16 metals form colored metal dithizonates, it is possible to classify them according to certain characteristic reactions so the metal present is restricted to a small group. Copper, bismuth, mercury, silver, gold, and palladium are the only metals that react in fairly acid solutions (pH equal to or less than 2.5), and impart violet, orange-yellow, orange-yellow, yellow, yellow, and brownish-red colors respectively to the carbon tetrachloride solution.

If certain "complexing agents" are added to a solution only a limited number of metals react with dithizone. The presence of cyanide (which

should of course be used in alkaline solutions only) restricts reaction of dithizone to lead, bismuth, divalent tin, and univalent thallium. In a slightly acid solution (pH 5) containing thiosulfate, only zinc, stannous tin, and palladium react. Ferrous iron forms a violet-red dithizonate at a pH 6 to 7, but ferric iron does not form colored dithizonates, although it tends to cause oxidation of the reagent and the formation of a yellowish-brown decomposition product soluble in the carbon tetrachloride phase, especially in alkaline cyanide solutions.

Although it would be of interest to know exactly what heavy metals were present in each sample tested and the precise amount, this information was not essential to a solution of the problem explored in the East Tintic district. It is sufficient for the present purpose to ascertain whether a correlation exists between our positive heavy metal tests of altered rock and blind ore bodies, and a concomitant relation between negative heavy metal tests in altered rocks and barren mineralization. The field method adopted was designed for rapid testing for significant heavy metals with only a low order of discrimination as to which metals were present. Later work with complexing agents indicated that zinc was the predominant heavy metal in most of the positive tests.

As both the ferric and ferrous iron in the rocks were essentially insoluble in ammonium acetate, the use of this solvent practically eliminated the interference due to iron. Observation of the carbon tetrachloride phase at a pH of less than 2 allowed discrimination between the copper group and the lead-zinc group; observation at pH 5 indicated whether the much more sensitive test at pH 9+ was essential. Complexing and reducing agents would be useful in detailed investigations, but would substantially increase the time required. They were not used in the field tests.

The colors of the metal dithizonates range from yellow through orange and red to violet, but are seldom sufficiently distinctive to narrow the choice to a single metal. In neutral and basic solutions the following colors are imparted to the carbon tetrachloride phase by the metal dithizonates named: violet from cobalt, ferrous iron, or silver; purplish red from zinc or mercury; cinnabar red from lead; red from cadmium, divalent thallium, or stannous tin; orange red from bismuth; yellow brown from copper; brownish gray from nickel. In the field tests made in the East Tintic district the colors in basic solutions were tints and shades of red or purple, probably owing chiefly to differing amounts of zinc and lead in the samples.

Interference.—Decomposition of dithizone is relatively slow in carbon tetrachloride solutions containing .02 per cent or more of dithizone, but in .001 percent solutions the dye is quite susceptible to heat and light and is easily oxidized. The brownish decomposition products greatly decrease the efficacy of the dithizone as a colorimetric reagent.

The occasional turbidity of the aqueous layer and slight oxidizing effects of colloidal ferric iron on the reagent appeared to be inconsequential for the purposes of the field work. Utmost care and caution were necessary in the handling and storage of the reagents, however. Almost hourly tests of their purity in regard to the heavy metals were found to be essential. Only those

lots of the "chemically pure" reagents were used that gave consistently little or no "blank," *e.g.,* color with dithizone. Contaminated lots were discarded or set aside for other use. The distilled water available from the local assayers, Brown & Brown, and Tintic Standard, was consistently heavy-metal free. Pyrex glassware, although preferable on the whole to other kinds of glass, appears to be responsible at times, despite careful cleaning, for a faint color in the blank, especially with the ammonium acetate buffers of alkaline pH. The practice adopted, therefore, was to use only solutions freshly prepared from concentrated reagents of previously ascertained purity. Both ammonium hydroxide and acetic acid in concentrated solutions appear to stand storage rather well, if properly protected from outside contamination.

FIELD TECHNIQUE.

Samples.—Sampling of rock outcrops was conducted on a predetermined grid with the following modifications:

Actual occurrence and distribution of the outcrops caused departures from the grid in some places. Sampling at some proposed sites had to be cancelled in the absence of accessible materials, and other sites transferred a short distance off the grid, according to need. This was especially true of the Tintic Standard area where houses, mine buildings, and dumps made it impossible to obtain many of the samples desired. Only the bedrock was sampled, not the mantle. The areas of bare rock surface range, roughly, from 25 to 10,000 square feet. Locations of the sampling sites are shown in Figs. 1, 3, and 4 within an accuracy of a few feet.

Every outcrop was sampled at about five points to obtain composite samples. The outer layer of every piece of rock to be composited was chipped off and discarded, leaving only clean cores. Hammers and pieces of iron employed were free from acetate-soluble heavy metals, as shown by the dithizone test.

Small pieces of rock, representing the site samples, were crushed in a diamond mortar, Plattner type, to the texture of a friable coarse sandy loam. It was found repeatedly with the highly significant negative tests that additional grinding to impalpability had no effect. Positive results with the reagent under field conditions were little influenced by variations in the amount of crushing, but on grinding to a rock flour in the laboratory the heavy metal content of the acetate extract increased materially, reflecting perhaps the increased access of the solvent to the syngenetic heavy metals present in the silicate minerals.

Extracting and Testing of Samples.—Approximately two grams, by weight or measure, of crushed rock was treated in a Pyrex beaker with about twenty cubic centimeters of distilled water and two cubic centimeters of concentrated acetic acid. This solution was brought to pH 5.5± by means of dilute ammonia, using "Hydrion" test paper. The resulting solution was approximately normal with respect to ammonium acetate. The beaker containing the sample and ammonium acetate solution was agitated gently for a half minute, the fines were allowed to settle for another half minute, and then the

solution containing as little suspended matter as possible was decanted into a glass-stoppered 100 cc. graduate of Pyrex glass. The crushed rock in the beaker was rinsed twice with small volumes of distilled water. The rinsings were added to the extract in the cylinder, and the total volume was made up to 50 cc. with distilled water.

The action of the ammonium acetate solution on the crushed rock is probably similar to the sodium acetate buffered, dilute acetic acid used by Morgan (8, p. 592) in his "Universal soil extracting solution." Morgan believes this reagent to be far superior to the unbuffered extracting solutions, such as simple mineral and organic acids, in the fractionation of the common elements in soils.

Five cubic centimeters of 0.002 percent solution of dithizone (weight per volume) in carbon tetrachloride was then added to the contents of the graduate. After an intensive shaking, the color of the carbon tetrachloride layer was noted. In the absence of colors indicating heavy metal at pH 5.5, the extract was brought to pH 9 ± with ammonia, as shown by the "Hydrion" test paper. After an intensive shaking, the color of the carbon tetrachloride layer was noted again. The solution was then brought to pH 2.5 ± by sulfuric acid, and again checked for metal dithizonates.

"Blank" determinations, where reagents only were carried through the testing procedure, were made at frequent intervals and were run concurrently with the test solutions.

Interpretation of Results.—Study of the results obtained in the Tintic Standard area, as well as general considerations of the problem, led us to use the intensity of dithizonate color as the criterion of mineralization, and to rely on this temporarily uncorrelated intensity of color as a guide to prospecting. Our problem in Tintic was simplified by a complete absence of colors on the acid side of pH 5.5 in 99 per cent of the extracts in both mineral and organic solutions (Table 2). Only 5 percent of the extracts of rock developed colors at a pH less than 7.0. This was in striking contrast to extracts of soils, plants, insects, and certain waters which were examined in the course of orientation studies in the district; these materials as a rule gave intense colors on either side of pH 5.5.

The usual absence of any color at pH 2.5 in the positive tests can be regarded as evidence of the practical absence of extractable copper, mercury, silver, bismuth, iridium, trivalent thallium, palladium, gold, and divalent platinum. The presence of metals other than zinc and lead in these positive tests is possible but seems improbable. It must be emphasized, however, that we searched for relationships between the color intensity and mineralization in the field reconnaissance, and not for any particular color of any specific dithizonate.

A relationship obviously exists between kind and intensity of the colors observed in the field tests and the amounts of extractable heavy metals present. For both judgment and expediency, however, we chose to rate color intensities by means of symbols rather than by numbers. Table 1 shows the relationship between color intensities, their field evaluation, and the concentrations of

TABLE 1.

APPROXIMATE RELATIONSHIP BETWEEN COLOR (2, 9) OF DITHIZONATES OF HEAVY METALS IN CARBON TETRACHLORIDE SOLUTIONS AND FIELD EVALUATION OF THE TEST. pH 8.5 FOR THE AQUEOUS PHASE.

Symbol (2, 9)	Color	Field evaluation	Possible heavy metal content (as Zn)
			Micrograms per aliquot
5R 4/10	Strong red	A+	5 and higher
5R 3/8	Dark red	A+	
5R 4/6	Moderate red	A	
5R 5/8	Moderate red	A	
5R 6/6	Light red	A to B	
5R 5/4	Weak red	A to B	
5RP 5/4	Weak red purple	B to C	5 to 0.2 and lower
5P 4/2	Weak purple	B to C	
5RP 4/2	Weak red purple	B to C	
5RP 4/6	Moderate red purple	B	
5RP 6/2	Pale red purple	C to D	0.2 to 0.1 and lower
5P 6/2	Pale purple	C to D	
5R 6/2	Reddish gray	C to D	
5YR 6/1	Light-brownish gray[1]	D to E	0.1 to 0.02
5Y 6/1	Light olive gray[1]	D to E	
5Y 5/2	Pale olive[2]	E to F	
5G 6/1	Medium-greenish gray[2]	F	
5G 5/2	Weak green[3]	0	apparently none
5G 3/2	Dusky green[4]	0	
—	"Reagent green"[5]	0	

[1] Color determined at pH 8.5; at pH 9+ the color is a light-pinkish gray (5R 8/2).
[2] Color determined at pH 8.5; at pH 9+ the color is a faint, very light pinkish-gray(5R 9/2).
[3] Color determined at pH 8.5+; at pH 9+ the carbon tetrachloride phase is colorless.
[4] Color determined at pH 8.5.
[5] Color at less than pH 8.5; color not exactly matched by color chart (9).

zinc, producing similar colors as determined later in the laboratory under similar conditions.

Strictly speaking, few, if any, of the color standards (9) named on our reference chart match the colors of the metal dithizonates in carbon tetrachloride solutions. Of necessity an element of judgment, interpolation, and adjustment enters the problem. For these and for other considerations Table 1 was composed with mental reservations to serve as a reference (subject to revision), and not as a guide in field work. Such references need modification and readjustment to fit them for each particular problem.

The use of letters to designate color intensities in large measure divorces the symbol from the quantitative significance that is custormarily sought. Unless the metal causing a color and the exact pH are known, however, the intensity can not be used quantitatively. Thus the molecular weights of zinc (65.38) and lead (207.20) indicate that the dithizone test for zinc should be slightly more than three times as sensitive as that for lead, if the color intensity of both metal dithizonates formed were the same. The color designations used, however, may be regarded as analogous to the customary "quali-

tatively quantitative" symbols used in spectroscopic analyses, where A + is equivalent to very strong; A, strong; B, moderately strong; C, moderate; D, weak; E, very weak; F, trace?; O, none.

Table 2 is included to show the frequency distribution of the various classes of positive tests and the proportion of tests in which the reagents ("blank") showed positive tests. The numbers of the samples reflect the chronological order in which they were tested, except for the accession number of the fresh rhyolite. Any subconscious desire to find positive tests where they might be expected was eliminated (as a factor influencing the judgment of dithizonate colors) by keeping the analyst in ignorance of the location of

TABLE 2.

CLASSIFICATION OF FIELD TESTS FOR HEAVY METALS ON BASIS OF INTENSITY OF COLORS DEVELOPED AT pH CA. 9.
Numbers refer to sampling sites.

Area	"O"	"F" (Trace?)	"E" (Very weak)	"D" (Weak)	"C" (Moderate)	"B" (Moderately strong)	"A" (Strong)	Very strong
"Tintic Standard"	3; 4; 5; 8; blank; 11; 13; 14; blank; 20; 22; 23; 24; blank; 26; 27; 32; 33; 35; blank	6[2]; 9; 17; blank; 19; 25; 34; 36; blank	2; 30	15; 16; 18; 31; 10R	4A	6[5]; 10; 12; 28; 29	7[5,6]	11; 7; 21
"Greyhound"	1; 2; 4; 5A[6]; 5B; 7; 8; blank; 11; 12; 13; 14; blank; 15; 16; 17	blank	6; 7; 10	9; 18		19		
"Chief Oxide"	1; 3; 4; 6; 9; blank; 20; 23; 24; 26; 28; blank; 29; 30; 33; blank; 34; 35; 36; 38; 42; 45; 46; blank; 47; 48; 51[2]	2; blank; 17; 18; 19; 21; 22; blank; 25; 31; 37; 50	5; 8; 16; 43; 44	14; 41; 49	15	7[5]; 11	12; 39[7]; 40	0[3]; 10[5]; 13
Fresh Packard Rhyolite	87-TL-45[8]	87-TL-45[9]						

[1] "E" at pH 2.5.
[2] Calcitic alteration.
[3] "F" at pH 2.5.
[4] Zn and Pb indicated by complexing agents in laboratory.
[5] Zn only indicated by complexing agents in laboratory.
[6] Rhyolite and monzonite, respectively.
[7] Brown red off-shade at pH 7.0 only.
[8] 40 ppm. Pb, and 100 ppm. Zn determined spectrographically.
[9] An E to F color developed on testing very finely pulverized material.

samples, and by using a random areal pattern for the numerical order in which the samples were brought in to be tested.

Field tests reported in Table 2 were confirmed on several occasions by different members of the group, with different lots of reagents and with the same lots, and with independently collected samples as well as with one and the same sample.

Negative fields tests, corresponding to the "O" and to many of the "F" color intensities, are significant by themselves in interpretation of the field results. The negative test indicates a practical absence of the soluble forms of zinc and lead, as well as of a number of other heavy metals, in the extracts of powdered rock. On the other hand, the negative test by no means indicates total absence of the heavy metals. Some lead and zinc, by virtue of their position in the crystal lattices of minerals such as biotite, are not accessible to the solvent action of ammonium acetate, under conditions of the field test, and do not produce colors with the dithizone. In a spectrographic analysis such inaccessible forms of zinc and lead are not distinguished from the more soluble forms, as, for example, that in the fresh unaltered Packard rhyolite 87–TL–45 and in some other samples subsequently examined. It can be easily seen, therefore, that in certain field problems the "fractionation" of a metal is more useful than a determination of its total.[3]

Positive field tests, corresponding to "A," "B," "C," "D," and "E" color intensities in their diminishing order, may be considered as a group, in contrast with the negative tests. These positive tests definitely indicate the presence of ammonium acetate soluble forms of heavy metals probably contained in sulfates, sulfides, carbonates, and other ore minerals, but they may also include traces of zinc and lead derived from the silicates in the crushed rock. As there is no correlation between the positive tests, even on roasting of the sample, with either sulfur or total iron (15), the metals responsible for the positive test, in all probability, are of later origin than the pyrite. Our present surmise is that these metals are due to hydrothermal activity later than the pyritic alteration. This interpretation finds support in the distribution of the positive tests with respect to the Tintic Standard ore bodies, as shown in Figs. 1 and 2.

RESULTS IN SELECTED AREAS.

A graphic summary of the field tests in three areas of pyritic alteration is presented in Figs. 1, 2, 3, and 4. In appraising the significance of these sample maps it is important to realize that each location shown represents a composite sample made up of many chips taken from different parts of an outcrop. Thus the number of tests should be multiplied by a factor of at least six to approximate the total number of individual samples used.

[3] The importance of fractionation, that is, of determining in what compounds or forms the metallic constituents occur in different parts of the regolith and of the biosphere, is of great basic and practical significance in geochemical reconnaissance and in geochemistry as a whole. Russian methods of prospecting by soil analysis (7, 11, 12, 13) use total methods only. It is believed that such work would have been far more productive if the possibilities of fractionation had been explored in these chemical studies of soils. A corresponding neglect on the part of our own investigators would be unfortunate.

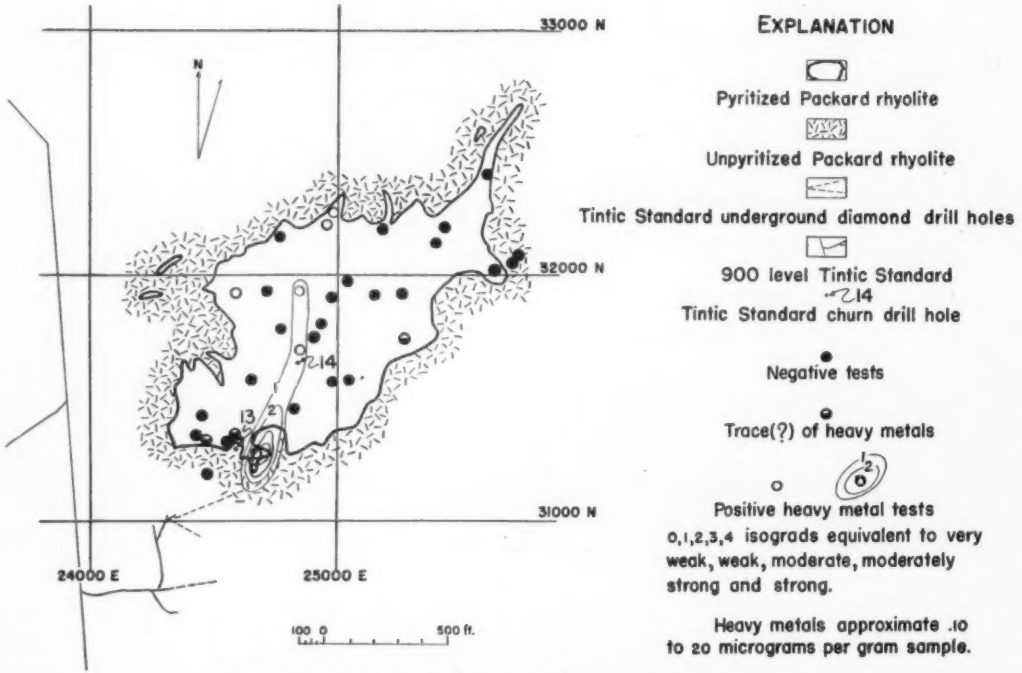

FIG. 3. Geochemical sample map of Greyhound alteration area.

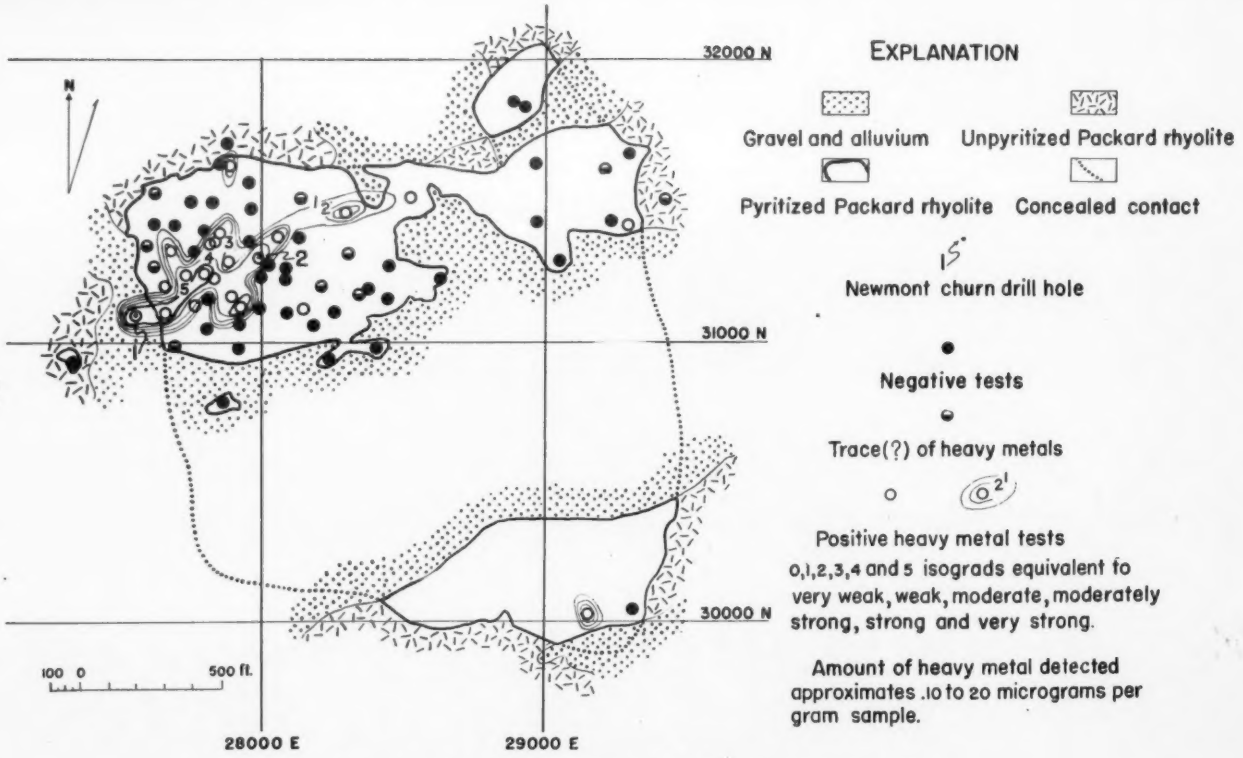

FIG. 4. Geochemical sample map of Chief Oxide alteration area.

Definite distribution trends are manifest in both negative and positive tests in the Tintic Standard area where the ore bodies, as shown in Figs. 1 and 2, are found at depths exceeding 600 feet. Geochemical studies alone, however, clearly would be inadequate to locate the ore bodies. In conjunction with the geologic investigations (6), however, wherein both sequence of the rock-alteration stages and detailed structure of the area were ascertained, the tests have a local significance that seems beyond dispute.

The Greyhound area (Fig. 3), where considerable exploration and drilling had been carried out in a late-stage pyritic-alteration zone, is comparable in many respects to the Tintic Standard area on the basis of surface geology. Drilling and underground openings indicate that no replacement ore is associated with this alteration zone, as the Tertiary volcanics here rest directly on the Lower Cambrian Tintic quartzite. Our geochemical tests showed little evidence of heavy metals; as shown in Fig. 3, there is some evidence of a mild concentration in a weak, narrow, transverse band in the west-central part of the area. The pyritic alteration in the Greyhound area was not followed, apparently, by appreciable metallization. It is probable that geochemical tests such as those shown in Fig. 3 would have discouraged deep drilling, had the significance of such tests been appreciated at the time of the exploration.

The Chief Oxide area, where for various reasons deep mineralization had been thought probable, presents an interesting contrast to the Greyhound area. A definite segregation of strong positive tests, as shown in Fig. 4, appears analogous to a similar segregation in the Tintic Standard area. One drill hole about 1,100 feet deep was begun some time before the start of the study. Another hole has been drilled since to a depth of about 1,100 feet. The holes, whose locations are shown in Fig. 4, are at opposite ends of the area containing the majority of the strong positive tests, but were stopped before penetrating the Cambrian Ophir formation, the chief producing formation of the district. The presence of a substantial zone of low-grade zinc mineralization in hole 1, together with the presence of much hydrothermal dolomite and some pyritic jasperoid, is of interest. Only further exploration at depth, however, will be adequate to establish whether the "geochemical high" found in this area reflects an ore body.

CONCLUSION.

A geochemical reconnaissance, based upon and associated with a detailed geologic study of the East Tintic district, Utah, indicates the desirability of testing certain types of altered rocks for an easily soluble fraction of the heavy metals present, as a guide to blind ore bodies. There can be little doubt that a purely geologic approach to the problem of ore finding can be profitably supplemented by studies of the kind reported here. Aside from its economic aspects, however, the technique devised should be useful in the problem of rock alteration in relation to subsequent mineralization.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
May 1st, 1948.

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PHOSPHATE DEPOSITS OF THE FORMER JAPANESE ISLANDS IN THE PACIFIC: A RECONNAISSANCE REPORT.

JOHN RODGERS.[1]

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ABSTRACT.

Fairly small phosphate deposits on several of the former Japanese islands in the Pacific produced about one-quarter of the phosphate rock used in Japan in the decade before World War II. During the early part of the war, the Japanese increased production greatly and gutted most of the deposits. Later in the war, most of the mining installations were badly damaged. Only Kita-daito, which was relatively undamaged, and Angaur, which has relatively large high-grade reserves, have even marginally economic deposits under present conditions.

Most of the deposits occur as an irregular mantle of phosphate or phosphatic clay over and between bizarre pinnacles of raised limestone. Phosphatic solutions from bird droppings attacked the limestone; further weathering and solution produced the phosphatic mantle and shaped the pinnacles. However the best deposits on Angaur are blanket deposits under swamps and apparently represent further alteration of deposits of the first type.

INTRODUCTION.

DURING the 1930's Japan consumed on the average more than 900,000 metric tons of phosphate rock per year. Most of this rock was converted into superphosphate fertilizer by reaction with sulfuric acid which has always been produced in abundance in Japan. However, practically all the phosphate rock was imported into Japan, for there are virtually no phosphate deposits on the four home islands. The only local deposit from which production is reported is one of phosphatic clay in Tertiary sediments in the vicinity of Takahama, Hagui-gun, Ishikawa-ken, on the Noto peninsula of Honshu Island. The material mined is reported to average only 13 percent P_2O_5 on a dry basis al-

[1] Published by permission of the Director, U. S. Geological Survey, and presented at the Twenty-seventh Annual Meeting, Society of Economic Geologists, New York, March 1947.

though it contains 40 percent water. The total recorded production of phosphate rock from the locality is 11,700 metric tons, produced from 1939 to 1945.

Before 1940, Japanese imports of phosphate rock were derived from four principal sources: Japanese islands in the Pacific, other islands in the Pacific, North Africa, and Florida. Each of these contributed roughly a quarter of the total imports. With the coming of war, Japan was cut off from the last three sources. To offset these losses, production from the Japanese islands in the Pacific was greatly increased (doubled between 1936 and 1942), and substantial imports were made from newly-developed sources on the mainland of east Asia. Nevertheless total imports decreased rapidly and steadily after 1940 and stopped in 1946.

The present paper deals only with the former Japanese islands in the Pacific. Production is recorded from sixteen different islands scattered from the Marshall group to the South China Sea, but the seven important producers lie around the Philippine Sea (Fig. 1). The production is given in the following table. Of these islands, only Angaur has produced on a scale at all comparable with the outstanding Pacific island deposits: Nauru and Ocean, northeast of the Solomon Islands, and Makatea, north of Tahiti.

PHOSPHATE ROCK PRODUCTION FROM FORMER JAPANESE ISLANDS IN THE PACIFIC, 1932 TO 1944 INCLUSIVE

Island	Production: 1932–1944 (in thousands of metric tons)	Year of first production
Angaur (Palau Islands)	1,217	1909 (German)*
Kita-daito (east of Okinawa)	503	1918**
Okino-daito (east of Okinawa)	486	1933
Fais (Caroline Islands)	283	1938
Rota (Marianas Islands)	236	1937
Peleliu (Palau Islands)	136	1935
Saipan (Marianas Islands)	88	1938
Other islands	119	——

* Taken over by Japanese in 1914, with only a few months break in production.

** Total production since 1918 is approximately 703,000 metric tons.

Source: Report No. 12, Natural Resources Section, General Headquarters, Supreme Commander for the Allied Powers, 1945 (also Report No. 44, 1946).

In late 1945 and early 1946, while assigned by the U. S. Geological Survey to the Natural Resources Section of General Headquarters of the Supreme Commander for the Allied Powers in Japan, I studied the phosphate situation in Japan from the point of view of raw materials. In the course of this study, I made a trip around the Philippine Sea, visiting briefly each of the seven deposits listed in the table except Kita-daito. The information in this paper is derived from my observations and from data assembled by the Natural Resources Section in Tokyo. The helpful interest and encouragement of many members of the Section is gratefully acknowledged, especially that of Lt. Col. Hubert G. Schenck, chief of the Natural Resources Section, of Thomas A. Hendricks of the U. S. Geological Survey, of Edward Sampson of Princeton University, and of C. R. L. Swanson, presently of the Connecticut Agricultural Experiment Station. I also wish to thank Josiah Bridge, Thomas A. Hendricks, and Frank C. Whitmore, Jr. of the U. S. Geological Survey for critical reading of the manuscript.

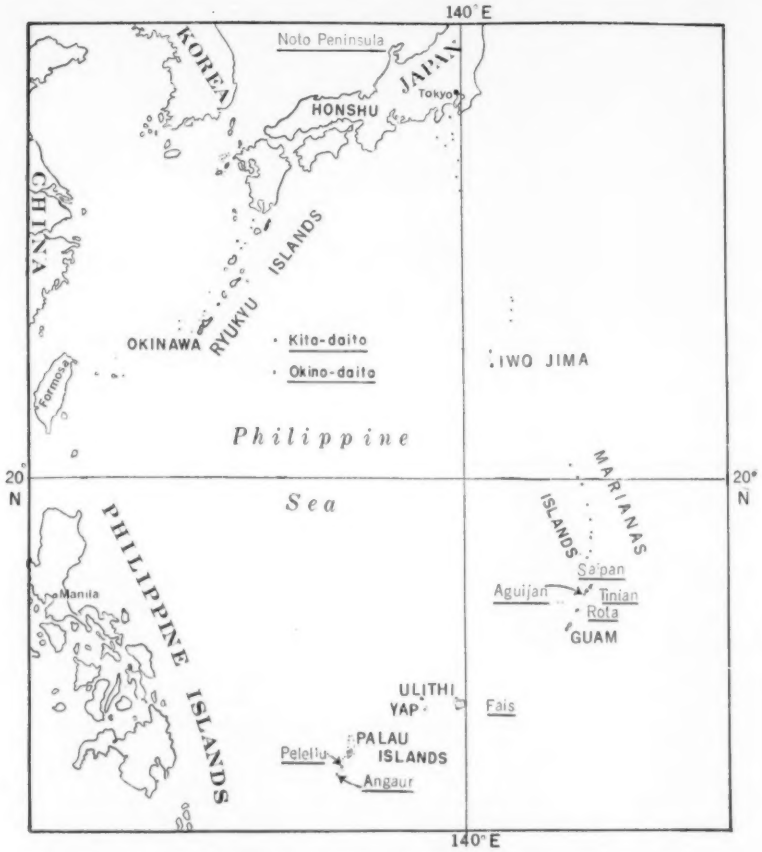

FIG. 1. Sketch map of vicinity of Philippine Sea. Names of principal phosphate islands are underlined.

THE PHOSPHATE DEPOSITS.

In all the deposits here described, the phosphate rock is produced from residual clay overlying reef and lagoonal limestone deposits which have been raised well above sea level. Deposits are known on some coral islands in the Pacific that have not been elevated, but all such deposits are smaller than the deposits here considered. Except on Kita-daito, the phosphorus is entirely in the form of calcium phosphate.

Fais.—The island of Fais in the western Carolines (Fig. 2) illustrates well the typical features of the phosphate deposits. The island consists of an

elliptical plateau of limestone half a mile wide and a mile and a half long. The surface of the plateau is about 50 feet above sea level and breaks off to the sea in cliffs in some places, in gentler slopes in others. Where not disturbed by mining, the surface of the plateau is flat with occasional low outcrops of limestone, but the surface of the limestone itself, under the mantle of residual clay and soil, is a forest of bizarre pinnacles that average 1 to 2 feet across and 3 to 4 feet apart. The crevices between these pinnacles are at least 6 feet deep and many are probably much deeper. This exceedingly irregular

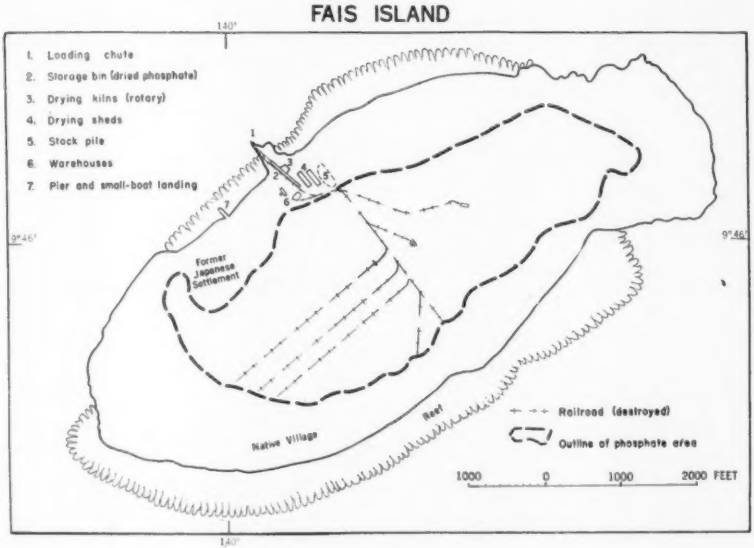

FIG. 2. Sketch map of Fais, Western Caroline Islands.

surface is believed to have been formed by the normal processes of weathering and solution that attacked the limestone under the soil cover, for it resembles closely, except in scale, surfaces that are present in limestone beneath soil and residual clay in warm humid parts of the United States such as Missouri and Tennessee. If this view is correct, the pinnacled surface was never exposed at the surface of the ground until mining operations commenced.

The clay filling the crevices between the pinnacles is the "phosphate rock" that is mined; it consists partly of hard gray and pink rounded grains about the size of bird-shot and partly of softer clay material. Apparently the hard grains are fairly high-grade phosphate and the softer material is lower grade. The average grade of the material mined was about 30 percent P_2O_5. Some hard crustified phosphate rock occurs plastered on the rough surface of the limestone pinnacles, but this was not mined.

Because the phosphate-bearing crevices are small the clay was mined by hand with the aid of a three-bladed post-hole digger. It was then loaded into cars running on narrow-gage tracks at the level of the original land surface (about the level of the tops of the pinnacles), and hauled to the plant which was near the middle of the northwest side of the island at the base of the prominent point on that side. The phosphate was dried in rotary kilns and stored for shipment. From the storage bins, the phosphate was hauled in other cars out onto the point, which projects into fairly deep water, and was chuted into 25-ton lighters.

The plant has been completely wrecked by bombing and subsequent exposure to the weather. A number of piles of phosphate were left scattered through the mining area, and since the Japanese departed, the natives have been dumping this material back into the crevices from which it was mined, thus restoring the original land surface on which they have planted gardens.

Rota.—The deposit on Rota resembles that on Fais in most particulars, but the plateau on which the phosphate occurs stands at 1,500 feet above sea level instead of 50. This plateau is the highest part of Rota, except for a low swell on one corner of the plateau which rises about 50 feet higher and is composed of igneous rock; wide, lower benches of limestone occur on all sides down to the sea, but no phosphate has been found on any of them. If Rota should be submerged 1,450 feet, it would resemble Fais almost completely. The phosphate seems to be similar, though with less bird-shot material and more clay. It is reported to average about 25 percent P_2O_5.

Operations differed from those on Fais only in that the phosphate was transported from the high plateau to the plant, which was close to shore, by means of an aerial tramway, and that loading was in shallower water. The tramway is now in ruins after much bombing. The mining area is abandoned and is overgrown with vines and other vegetation.

Saipan and Adjacent Islands.—After the American occupation of Saipan in 1944 the sites of former phosphate mining were completely filled in and converted into military installations. Hence, nothing could be seen of the deposits, although they probably resembled those on Fais and Rota. The sites are on a bench of limestone about 50 feet above sea level that surrounds the precipitous north and west faces of Mount Marpi at the north end of the island.

Phosphate deposits were also reported on the islands of Tinian and Aguijan, south of Saipan, but they were not visited. According to Japanese data, the main deposit on Tinian lies in the Marpo Basin just northwest of Carolinas Hill, the highest point on the island, which is a plateau in the southeastern part; other deposits lie on a lower plateau in the northwestern part of the island. The deposit on Aguijan is on the flat plateau 200 feet or so above sea level that constitutes most of the island; no part of Aguijan projects higher. The deposits on Saipan, Tinian, and Aguijan are reported to average between 20 and 25 percent P_2O_5.

Okino-daito.—Okino-daito is a fairly round island about 1½ miles across; it slopes to the sea on all sides without cliffs but with rough rocky shores. The phosphate deposits underlay the central part of the island, which before

mining was either flat or a shallow basin. As on Fais and Rota, the phosphate occurs in clay in crevices between pinnacles of limestone, but on Okino-daito the pinnacles and crevices are on a much larger scale, being 5 to 15 feet wide and 20 to 30 feet apart, and standing as much as 50 feet high. The phosphate was mostly clayey material, but considerable hard crustified phosphate was plastered against the sides of the pinnacles and this material was collected separately during mining. The phosphate from Okino-daito averages 25 percent P_2O_5 or a little better.

Because of the larger size of the crevices, haulage tracks were carried down into the deposit level by level as mining proceeded. At each level the tracks were laid out in fairly straight lines through the deposit, often through pinnacles, and the clay between the pinnacles and above the track level was mined out on all sides. As lower levels developed, the higher haulageways were not removed but left suspended, as it were. The result is a tangle of haulageways criss-crossing in three dimensions through a forest of irregular and commonly overhanging pinnacles up to 50 feet high. At least seven-eighths of the deposit has been excavated.

The drying plant is similar to those on Rota and Fais. A large concrete pier 20 feet high projects into deep water on the west side of the island close to the plant; on the north side of the pier is a slip where smaller boats were hauled up by a winch. All machinery has been badly damaged by bombing and shelling.

Kita-daito.—Kita-daito was not visited but an interesting report on the deposits of the island, published in 1935,[2] was available. Although small bodies of phosphate rock like that on Okino-daito occur on the highest part of the island and on a lower hill in the northwest corner, the main deposit and the only one mined consists of aluminum phosphate. It underlies clay deposited in a former lagoon now uplifted about 130 feet above sea level. A great mass of andesitic pumice, presumably from the explosive eruption of some one of the Japanese or Philippine volcanoes, was washed into the lagoon before the uplift; aluminum leached from the pumice by weathering after the uplift is believed to have converted a former deposit of more normal phosphate into the existing aluminum phosphate. The material shipped contains 20 to 30 percent P_2O_5 and as much as 40 percent Al_2O_3.

The plant and pier on Kita-daito resemble those on Okino-daito. Kita-daito was little affected by the war, and some shipments were made from the island in 1946, apparently from earlier-mined stocks.

Angaur.—The phosphate deposit on Angaur is the most productive and the highest-grade deposit in the former Japanese islands. Angaur is an irregularly triangular island, whose northwest part stands somewhat higher than the rest. This portion consists of several swampy basins separated by rather gentle ridges on which limestone crops out. The crevices are larger than those on Fais and Rota, but smaller than those on Okino-daito; they average perhaps 5 feet wide and 10 to 25 feet deep.

[2] Yamanari, Huzima, Aluminum-phosphate deposit in Kita-daito-zima: Research Contributions of the Institute of Paleontology, Department of Science, Tohoku Imperial University (Sendai, Japan), No. 15, 1935 (In Japanese).

Two types of phosphate are present. The first type, red or brown phosphate, fills crevices between limestone pinnacles under the ridges and consists almost entirely of hard grains like bird-shot that are considerably harder and darker in color than the similar grains on Fais. Little clay is present, and as a result the shot-like material is like loose coarse sand. The red phosphate is of high grade though it contains considerable iron. It is reported to be nearly worked out.

The second type, white phosphate, occurs in continuous blanket deposits under the swamps. Apparently the thickness of the blankets ranges gradually and regularly from 15 feet or even more in the centers of the swampy basins to 3 or 4 feet at the edges. The material is gray and clayey but commonly shows traces of pisolitic texture. The moisture content is high, but after drying the white phosphate is of higher grade than the red phosphate. Estimates of reserves (1946) ranged from half a million to 2½ million tons of white phosphate, averaging between 35 and 40 percent P_2O_5.

The red phosphate on Angaur was mined by hand, but the white phosphate was mined by floating mechanical dredges employing sand pumps. The white phosphate was dried in the sun after mining; both kinds were then dried in rotary kilns before shipment. A special mechanical loader on the pier apparently permitted loading direct into ocean-going ships. The loader is in bad repair and the drying plant was nearly destroyed by bombing and shelling.[3]

The deposit on Peleliu, just north of Angaur, apparently contained material like the red phosphate on Angaur, but is reported to be practically worked out. Much of the mining area was converted into military installations after the American occupation.

ORIGIN OF THE DEPOSITS.

A few generalizations can be made concerning the phosphate deposits. As already noted, all occur in residual clay overlying or between pinnacles of upraised limestone. Some of the islands on which they occur show evidence of repeated uplift. Many of the deposits occur on the highest parts of their respective islands, but this is not true for Saipan or Tinian. There is a tendency for deposits to lie in the northwest parts of the islands, especially where they do not lie on the highest parts, but again there are exceptions. Finally, none of the islands are now frequented by birds to the extent that droppings are accumulating.

That bird droppings were the original source of the phosphorus in these deposits is not questioned. However, the considerable rainfall on these

[3] Josiah Bridge of the U. S. Geological Survey supplies the following information: Shipping of phosphate to Japan was resumed in August 1946. The J. A. Pomeroy Company, operating under a contract with the U. S. Navy, began moving the phosphate rock from the stockpiles to the coast, where it was taken over by the Japanese and loaded and shipped to Japan in U. S.-owned ships manned by Japanese crews. Later in the year the loading boom was torn down and replaced by a new one, and the actual mining of phosphate was begun. The Pomeroy contract terminated on June 30, 1947, at which time the entire operation was taken over by the U. S. Army which is using Japanese labor for all operations. The driers and the storage house are still unserviceable and all phosphate is being shipped wet.

islands is now unfavorable to the accumulation of guano as such. It is believed that the rain water dissolves out phosphoric acid from former deposits of guano and carries it down into the underlying limestone. The acid attacks the limestone in accordance with the following equation:

$$2H_3PO_4 + 3CaCO_3 \rightarrow Ca_3(PO_4)_2 + 3H_2O + 3CO_2.$$

The phosphoric acid would be concentrated enough to attack the limestone only above the water table; hence the restriction of such deposits to raised coral islands.

The calcium phosphate formed would be deposited at the surface of the limestone. This is presumably the origin of the hard crusts of phosphate on the pinnacles. However, ordinary weathering and solution of the limestone proceeds at the same time as phosphate formation; hence the calcium phosphate originally deposited at the limestone contact would soon be left behind in the residual clay. The relative speed of the two processes would in part determine the proportion of phosphate to clay impurities. As the impurities in the limestone are small in amount, the resulting mixture is commonly a phosphate ore.

The process by which the phosphate is converted into hard shot-like grains is more obscure. Perhaps it is similar to formation of pisolitic texture in bauxite and lateritic limonite. The grain structure is especially well developed in the iron-bearing red phosphate of Angaur. The white phosphate of Angaur apparently represents an additional complication; perhaps the iron content of red phosphate bodies that underlay swamps was leached or reduced so that the grain structure broke down and the color was changed to gray or white.

ECONOMICS OF THE DEPOSITS.

In the late thirties, the Japanese made an exhaustive search for phosphate deposits in the islands under their control. Thereafter they worked all the significant deposits discovered, regardless of cost. Thus most of the deposits, which were originally rather small, have been practically exhausted under uneconomic conditions. Moreover many of the islands were fought over or heavily bombed during the American advance in 1944 and 1945. It is believed therefore that only two of the deposits possess any promise of future production. Kita-daito did not suffer much from war damage, and production on the order of tens of thousands of tons a year could probably be resumed there, but the material produced is low-grade and of unusual composition. Angaur is the only deposit with economic reserves of high-grade phosphate. However, the deposit must be mined by dredges and the old machinery is useless. The cost of the new equipment necessary to mine, dry, and load the ore places this deposit in a marginal if not uneconomic class.

YALE UNIVERSITY,
NEW HAVEN, CONN.,
May 3, 1948.

A PARTIAL STUDY OF THE NiAs–NiSb SYSTEM.

D. F. HEWITT.

ABSTRACT.

Artificial niccolite and breithauptite were synthesized and thermal studies of the NiAs–NiSb system show that nickel arsenide and nickel antimonide form a complete solid solution series in one another.

The change in cell dimensions is reflected in the regular change in powder diffraction patterns from NiAs to NiSb. Graphs are given for the calculation of the composition of the various members of the series by comparison of the X-ray powder diffraction photos.

INTRODUCTION.

THOUGH the minerals niccolite and breithauptite have long been considered as grading from one to the other and the name "arite" has been given to so-called intermediate varieties, the striking occurrence of both niccolite and breithauptite in close contact in single specimens of Cobalt silver ores suggested that a thermal study of the relations of these minerals should be worth while to test their solubility in each other.

Niccolite is a minor constituent of some of the Sudbury ores where it is associated with gersdorffite, maucherite, chalcopyrite, pentlandite and pyrrhotite. No analyses for antimony are available from such occurrences. In the silver-bearing veins of Cobalt, Ontario, niccolite and breithauptite are found in close association with cobaltite and other cobalt arsenides. Arite is described from France, near Eaux-Bonnes, Basses Pyrénées.

Structure of Niccolite and Breithauptite.—Niccolite and breithauptite have the B–8 nickel arsenide structure, first analyzed by Aminoff in 1923. In this structure each nickel atom is surrounded by six arsenic atoms, and each arsenic atom by six nickel atoms. The nickel atoms are distributed on a simple hexagonal lattice; the arsenic are distributed differently on two hexagonal lattices which are roughly in the relation of hexagonal close packing (1) [1]. The result is a structure with alternate layers of nickel atoms and arsenic atoms.

Cell dimensions of breithauptite are slightly larger than those of niccolite. Dana's System of Mineralogy gives the following figures:

Niccolite: $a = 3.602$, $c = 5.009$, $c/a = 1.3905$.
Breithauptite: $a = 3.938$, $c = 5.138$, $c/a = 1.305$.

The similarity of the two lattices and of the sizes of arsenic and antimony atoms (for the elements, arsenic—1.25 Å, antimony—1.45 Å) suggests according to Goldschmidt's rule that a wide range of solid solutions should be expected.

[1] Numbers in parentheses refer to Bibliography at end of paper.

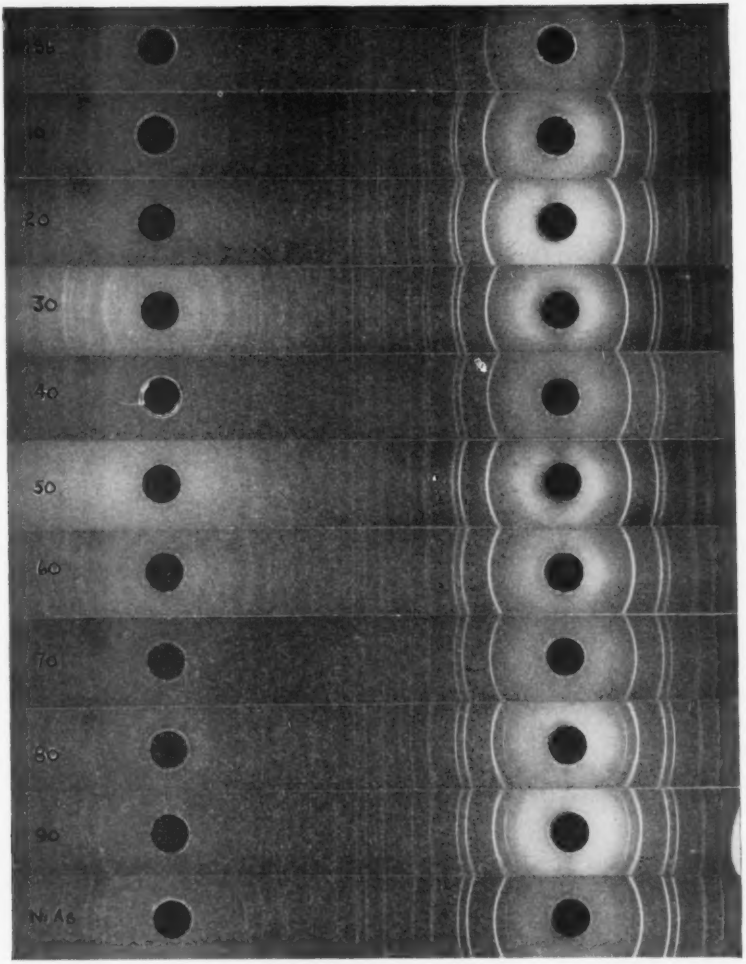

FIG. 1. Powder photos NiAs–NiSb system, CuKα radiation, camera radius $90/\pi$ mm reduced from contact prints of film. Fine maucherite lines in lower three photos.

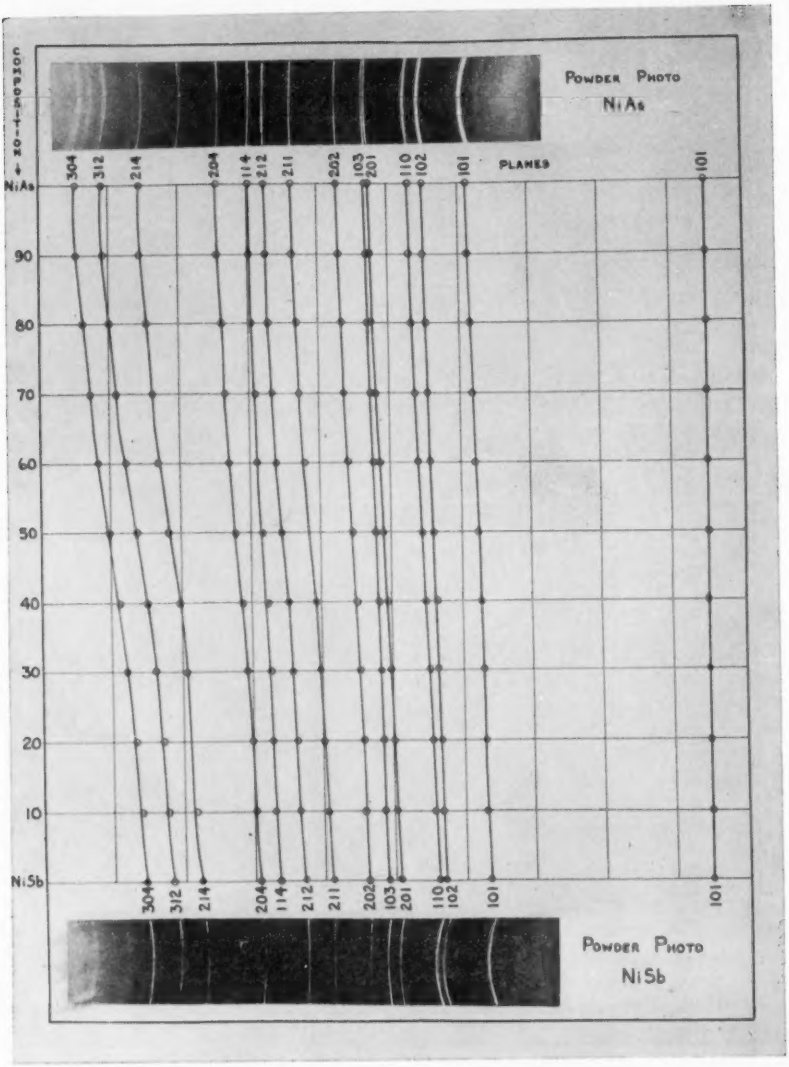

FIG. 2. Graphical representation of change of Θ for various planes with change of composition.

Experimental Procedure.—The materials used for these experiments were chemically pure powdered metallic nickel, arsenic and antimony which were mixed together in various atomic proportions ranging from pure NiAs to pure NiSb. The charges, weighing one gram, were placed in silica glass tubes, evacuated and sealed. These were heated in a Lindberg furnace to the temperatures required for reaction and slowly cooled. Annealing of the homogenized products at low temperatures was carried out in most cases.

The fusion products were split, one part was polished and examined under the metallographic microscope, the other parts were available for X-ray work and density measurements on the Berman balance

EXPERIMENTAL RESULTS.

Members approximating the compositions NiAs; 90NiAs·10NiSb; 80 NiAs·20NiSb; 70NiAs·30NiSb; 60NiAs·40NiSb; 50NiAs·50NiSb; 40 NiAs·60NiSb; 30NiAs·70NiSb; 20NiAs·80NiSb; 10NiAs·90NiSb and pure NiSb were synthesized. The resulting solid solutions were stable at room temperatures.

Examination of X-ray powder films of the components of the series taken on cylindrical camera with radius $90/\pi$ mm shows the change of cell dimensions reflected in the regular change in powder pattern from NiAs to NiSb (Fig. 1—Powder photos—NiAs·NiSb). Fig. 2 gives a graphical representation of the gradual change in the spacings of the lines on the x-ray powder films, representing the change of Θ for the various planes in the crystal structure with change in composition. An obvious use which might be made of this diagram is the ready determination of the composition of natural niccolites and breithauptites from powder photographs.

It will be noted from Fig. 2 that the values of Θ decrease (*e.g.*, plane 10.1), going from the NiAs end to the NiSb end. The slope of the lines gives the rate of change of Θ. These rates of change vary for the different planes; for example, the lines for planes (11.0) and (10.2) converge, while those for planes (10.3) and (20.1) diverge. This confirms the fact that the c/a ratio changes from 1.390 for pure NiAs, to 1.308 for pure NiSb.

Variation in Lattice Parameters.—The values of a and c for the lattice were calculated from measured Θ angles by simultaneous solution of the quadratic equation for two values of $(h\ k\ l)$:

$$\sin^2\theta = \frac{\lambda^2}{4}\left[\frac{4}{3}\frac{(h^2 + hk + k^2)}{a^2} + \frac{l^2}{c^2}\right].$$

For these calculations a pair of diffraction rings with high values of Θ were used for each component of the series. Diffractions (31.2) and (30.4) were chosen with Θ values of 60 to 70 degrees.

Figure 3, curves 1, 2, 3 and 5, are graphical representations of the change of Θ for the planes (30.4), (31.2), (20.4) and (11.4), showing the increased sensitivity for the higher values of Θ. Table I gives the values of Θ for (31.2) and (30.4) used in the calculations, the values of a and c, the c/a ratio, and the cell volumes. Curves 7, 8 and 9, Fig. 3, show the changes of

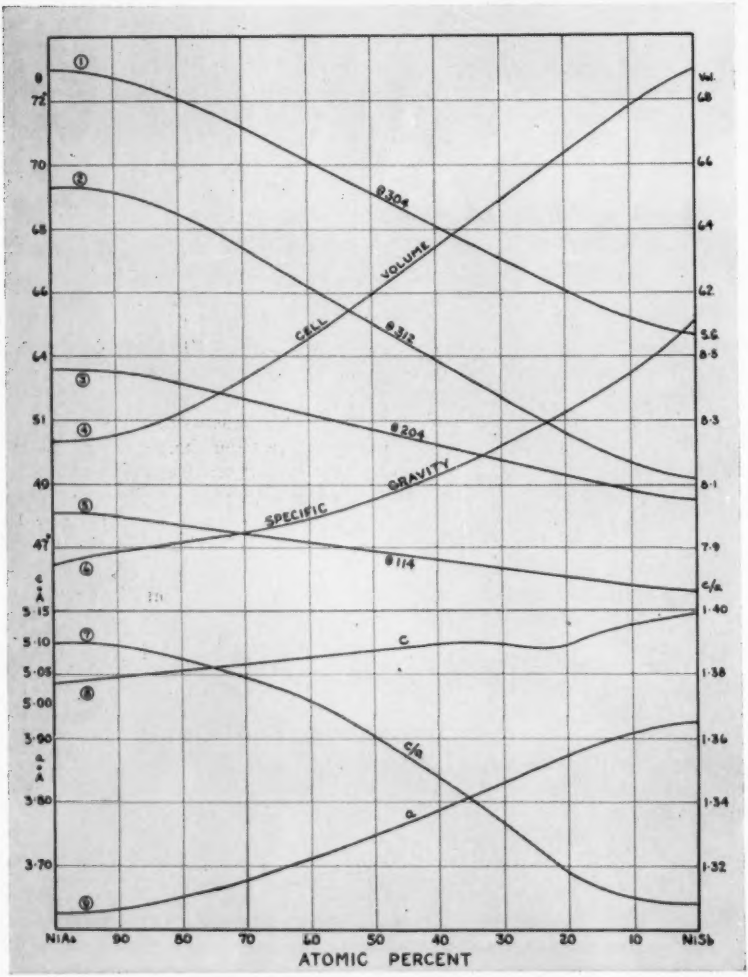

FIG. 3. Graphical representation of change of cell parameters with change of composition.

cell dimensions, a and c, and c/a ratio with composition. The change in cell volume and specific gravities are shown by curves 4 and 6.

Table I tabulates the change in cell dimensions as calculated.

The following conclusions are suggested by the data:

1. If we consider the structure to consist of a nickel lattice and a B sub-group metal lattice, it is apparent that the nickel lattice must accommodate itself to the change in dimensions of the B sub-group lattice. In other words, the nickel lattice is not rigid. The B sub-group lattice dominates the structure and when there is expansion of the As-lattice with addition of Sb atoms there is a change in cell dimensions to which the nickel lattice must conform.

TABLE I.

CELL DIMENSIONS, NiAs – NiSb SYSTEM.
Composition (Atomic Percent)

	Nat.	NiAs	90	80	70	60	50	40	30	20	10	NiSb	Nat.
No.		1097	1235	1236	1145	1272	1209	1181	1207	1208	1271	1116	
θ (30.4)		73 00	72 54	72 00	71 06	70 12	69 00	68 00	67 12	66 12	65 18	64 42	
θ (31.2)		69 18	69 12	68 18	67 24	66 24	65 00	64 00	62 48	61 36	60 48	60 12	
a	3.602	3.624	3.627	3.650	3.675	3.705	3.751	3.784	3.831	3.878	3.909	3.934	3.938
c	5.009	5.039	5.040	5.054	5.069	5.078	5.086	5.108	5.093	5.099	5.130	5.145	5.138
a/c	1.3905	1.390	1.388	1.385	1.380	1.370	1.358	1.350	1.330	1.315	1.312	1.308	1.305
θ (20.4)		52 36	52 30	52 06	51 48	51 24	50 42	50 12	49 48	49 18	48 48	48 30	
θ (11.4)		48 06	48 00	47 42	47 30	47 18	46 48	46 36	46 24	46 12	45 54	45 42	
Cell Volume		57.313	57.41	58.32	59.30	60.38	61.97	63.34	64.72	66.42	67.88	68.95	Cubic KX

$$\% \text{ increase in } a = \frac{.31}{3.62} \quad 8.6\%$$

$$\% \text{ increase in } c = \frac{.106}{5.04} \quad 2.1\%$$

2. With increasing Sb content there is a small increase of 2.1 percent in c from 5.039 to 5.145; at the same time there is a fairly large increase of 8.6 per cent in a from 3.624 to 3.934. Consequently the value of the c/a ratio shows a decrease from 1.390 to 1.308; the unit cell becomes more equant.

We have already noted that the nickel arsenide structure is a layered structure with alternate nickel and arsenic layers. With addition of antimony atoms to the arsenic layer there is little effect on the distance between arsenic and nickel layers, as reflected in the small increase in c. However, there is a considerable effect on the spacing of the arsenic-antimony atoms in one layer and the nickel atoms in the other, as reflected by the increase in a.

3. The rate of change of cell dimensions approximates a straight line, following Vegard's law. However, the values of a deviate noticeably from the straight line: curve 9. The rate of change of this lattice parameter is low at both ends of the system and high in the center. That is to say the expansion of the lattice is not as great for a ten percent increase of Sb content at the NiAs or NiSb ends as it is in the fifty percent region. This results in a curve that is concave upward at the NiAs end, convex downward at the

NiSb end. Also the rate of change of a is slower at the NiAs end than at the NiSb end of the system. This point is further brought out by curve 4 showing the change of cell volume with composition.

COMPARISON OF ARTIFICIAL AND NATURAL NICCOLITE AND BREITHAUPTITE.

Artificial NiAs and NiSb are identical with natural niccolite and breithauptite in structure. Table II gives the X-ray powder diagrams for artificial NiAs, niccolite from Hesse; artificial NiSb and breithauptite from Cobalt, Ontario.

TABLE II.

POWDER DIAGRAM DATA.

Natural Niccolite		Artificial Niccolite		Natural Breithauptite		Artificial Breithauptite	
No. 1098		No. 1134		No. 1116		No. 1131	
Int.	d	Int.	d	Int.	d	Int.	d
10	2.644	10	2.65	10	2.840	10	2.840
9	1.959	9	1.967	9	2.052	9	2.052
9	1.812	8	1.812	9	1.959	9	1.967
6	1.497	4	1.501	4	1.6161	3	1.611
6	1.479	4	1.479	2	1.561		—
7	1.330	4	1.333	4	1.533	2	1.524
2	1.257	2	1.259	3	1.415	2	1.415
5	1.149	4	1.151	1	1.286	1	1.283
6	1.069	4	1.068	3	1.248	1	1.246
3	1.043	3	1.046	2	1.206	2	1.203
6	1.031	4	1.033	2	1.149	2	1.149
3	0.967	2	0.969	2	1.138		—
1	0.956		—	3	1.076	3	1.070
2	0.904	2	0.904	2	1.028	2	1.023
3	0.856	3	0.856	3	0.982	1	0.982
1	0.847		—	1	0.927	1	0.927
3	0.820	3	0.820	1	0.886		—
2	0.810	2	0.810	3	0.850	1	0.848
4	0.802	3	0.803	2	0.826		
				2	0.803	2	0.801
				2	0.780	1	0.776

Hardness, color, anisotropism and etch reactions are the same for natural and artificial products.

NICCOLITE-BREITHAUPTITE RELATIONS IN ORES.

The results of the investigations of the NiAs–NiSb relations in artificial melts suggests that niccolite and breithauphtite may form solid solutions in one another and that "arite" may truly be an intermediate member in the series. However, examination of polished sections of Cobalt ores reveal that niccolite and breithauptite occur together. There are two possible explanations of their occurrence side by side:

1. The niccolite was introduced later and replaced the breithauptite to some extent. The paragenesis of the ore suggests that this may be the case. Ellsworth (2) states, "from the structural evidence it appears that breithauptite was the first mineral deposited accompanied by relatively small amounts of niccolite in microscopic included grains. After the precipitation of breithauptite had ceased the niccolite continued to come down and formed a thin layer over the arborescent breithauptite." It is interesting to note that Ellsworth's analyses of the breithauptite gives 0.58 percent As while the niccolite, which presumably may have replaced the breithauptite to some extent, contains 4.95 percent Sb, or about 7.5 percent NiSb.

2. Although niccolite and breithauptite may form a complete mix-crystal on crystallizing from a melt, it is possible that under very different, natural, physiochemical conditions of crystallization, probably at a relatively low temperature, from an *aqueous* ore fluid, mix-crystals do not form.

Further experiments on the crystallization of these minerals from aqueous media are needed. If a series of solid solutions can be formed under such conditions at lower temperatures than used in the present study, the individual occurrence of niccolite and breithauptite in the one ore as at Cobalt would clearly be ascribed to the later introduction of one compared to the other and a real age difference would be indicated rather than simply successive deposition from one ore fluid, a very common and vexing problem met in paragenetic studies.

STABILITY OF NiAs AND SOME Ni(As,Sb) SOLID SOLUTIONS AT HIGH TEMPERATURES.

As discussed in a separate paper (3), in synthesizing NiAs and solid solutions containing up to 30 atomic percent NiSb, arsenic was lost with the formation of Ni_3As_2 by partial dissocitation.The reaction involved, first noted by Vigouroux (1908), is described by Hansen (4) as a peritectic reaction and apparently was not taken into consideration by Friedrich (5) in his investigations of the Ni-As system.

Temperatures at which dissociation occurs vary with the pressure. While no attempt has been made to determine equilibrium conditions, our experiments indicated that while partial dissociation occurs above 800° C, in evacuated sealed tubes, slight dissociation also takes place over periods of 20 hours when NiAs is heated between 450° C and 500 ° C.

Friedrich's phase diagram for the Ni-As system should accordingly be modified to show NiAs melting incongruently to Ni_3As_2 and As vapor at temperatures ranging upward from about 500° C.

The correspondence between the artificial Ni_3As_2 which forms striking intergrowths with NiAs or Ni(As, Sb) (described elsewhere) and the natural mineral maucherite has been shown both by standard etch tests and by X-ray analysis. Table III gives the powder diagram for natural maucherite reported by Peacock (6), natural maucherite from Sudbury, and the artificial maucherite (Ni_3As_2) produced by heat treatment of NiAs. Peacock has shown that maucherite has a defect lattice structure with the probable con-

tent of the pseudo-cell $Ni_{12-1}As_8$ or 4 (Ni_3As_2)-Ni. The exact composition of the maucherite-like phase produced has not been determined, but the correspondence of the stronger lines and many of the weaker lines to values obtained by Peacock and to those obtained on Sudbury maucherite in our laboratory is sufficiently great to show they are essentially the same substance.

TABLE III.

POWDER DIAGRAMS—MAUCHERITE.

Maucherite (Peacock)			Maucherite-Sudbury		Artificial Maucherite	
			No. 1115		No. 1150	
Int.	*d*	(*hkl*)	Int.	*d*	Int.	*d*
S	2.70	008	10	2.691	10	2.706
W	2.36	112	4	2.385	3	2.385
S	2.02	116	9	2.025	8	2.026
VW	1.979	019	6	1.9048	8	1.967
W	1.819	0.0.12		—	2	1.825
S	1.717	020	8	1.7227	7	1.728
W	1.621	1.1.10	3	1.6267	2	1.627
W	1.508	0.1.13	2	1.510	2	1.510
S	1.447	028	5	1.454	(2	1.479
VW	1.362	0.0.16	2	1.367	(1	1.454
VW	1.297	129		—		—
VW	1.243	0.2.12		—		—
M	1.211	220	5	1.216	3	1.213
M	1.131	1.2.13	2	1.113	1	1.131
M	1.104	228	3	1.108	1	1.103
M	1.081	1.1.18	3	1.085		—
W	1.065	0.2.16	3	1.070		—
W	1.042	136	2	1.044	1	1.036
VW	0.988	0.3.11		—		—
W	0.970	1.3.10	2	0.974		—
W	0.942	0.3.13	1	0.945		— (not
VW	0.927	235	1	0.930		— measured)
VW	0.914	0.1.23	2	0.909		—
W	0.904	2.2.16		—		—
W	0.889	1.3.14		—		—
W.	0.858	040	2	0.859		—
VW	0.847	1.3.16		—		—
W	0.827	141	2	0.827		—
W	0.817	048	2	0.819		—
W	0.807	0.3.19	1	0.807		—
W	0.802	0.2.24	2	0.803	1	.8046

For a further discussion of the resulting textures shown by NiAs, Ni (As, Sb) solid solutions and Ni_3As_2 the reader is referred to the paper cited above, but the fact may be noted here that addition of antimony to beyond the ratio of 70NiAs : 30NiSb stabilizes the lattice of the resulting solid solutions and no dissociation occurs even at temperatures of over 1100° C.

The writer gratefully acknowledges the assistance of Dr. J. E. Hawley and Dr. L. G. Berry of Queen's University, under whose direction the work was carried out.

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KINGSTON, ONTARIO,
April 1, 1948.

FIELD METHODS: ATEMPORAL POLARIS CORRECTION.

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ABSTRACT.

Methods of determining true north from the azimuth of Polaris whenever the angular elevation of Polaris and any other identified star can be measured simultaneously, are here outlined: the method described in detail for the star Mizar (Zeta Ursae Majoris), for which working constants are given; and outlined for Ruchbah (Delta Cassiopeiae), with working constants. Basic theory is given, but is accompanied by specific instructions for rapid determinations under field conditions.

INTRODUCTION.

THE azimuth of the Pole Star (Polaris, or Alpha Ursae Minoris) never differs from true north by more than 63 minutes of arc, because that star describes a circle of this radius about the north celestial pole (a northward extension of the Earth's axis) once each sidereal day (of 23 hours, 56 minutes, 4.091 seconds of mean solar, civil, or "clock" time). In consequence, if the orientation of a survey is based on an uncorrected Polaris azimuth, the maximum error due to lack of Polaris correction will not exceed 63 minutes of arc, and the probable error will be half of this. This error, in many instances, is less than that produced by undetected compass deviation.

Because the motion of the Earth in its orbit about the Sun is substantially uniform and periodic, its position at any time can be predicted with great accuracy. In addition, the spatial relations of the stars, including the Sun, are definitely known to a high degree of accuracy, and change so slowly that, for purposes of ordinary surveying, they may be considered invariant. In consequence, terrestrial positions can be, and are, determined with great accuracy by means of stellar observations.

In general, when the relation of a stellar configuration to a terrestrial parameter (such as the horizon) is known, the angular relation of Polaris (or any other identified star) relative to that parameter and the celestial pole can be determined by a simple computation; and from this, true north and the latitude of the observer can be found directly to any accuracy ordinarily desired (to and beyond seven significant figures).

The foregoing relations, augmented by a second independent observation, to give an intersection, or "fix," form the basis of the science of navigation. Abridged navigational procedures are commonly used to locate true north in the field.

PROCEDURES IN COMMON USE.

Where true north must be determined with greater certainty than is obtainable by correcting magnetic north for supposed local deviation (also

called declination by some authors), or where local magnetic attractions are suspected, two navigational methods are in common use. The first and simplest, outlined by Lahee,[1] is perhaps the best known, and although it contains a small theoretical error, of a few seconds of arc, it has proven quite satisfactory in many field surveys.

This first method of determining true north depends upon the invariance of stellar configurations (Fig. 1). It has been found by observation that whenever a line through the stars Mizar (in Ursa Major) and Ruchbah (in Cassiopeia) is vertical, regardless of which star is "on top," Polaris is substantially on the local meridian, and hence that its bearing is true north (with an ordinarily negligible error).

This method is simple in both theory and practice, but the necessary relations occur only twice in each 24 hours, and may be observed (usually) only once, as the stars are quite difficult to locate in the daytime. In addition, the method is unworkable at latitudes less than about 35°, because either Mizar or Ruchbah is below the horizon, and hence not visible; and the determination of verticality becomes quite difficult at latitudes greater than about 70°. Chief objection to this method is the long wait occasionally necessary for the proper stellar orientation.

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A second method, not so commonly used, but workable through a wide range of north latitudes (roughly from 5° to 70°), is based on the same general relations (Fig. 1) as the first, and has the same time relations. Because a line through Polaris and either Mizar or Ruchbah becomes vertical about 23 minutes before Polaris transits the local meridian, the time of this transit, and hence the instant at which the azimuth of Polaris is true north, can be determined quite accurately. Complete instructions for this determination are included annually in the *American Ephemeris and Nautical Almanac* (Table VI) prepared for each year, in advance, by the U. S. Naval Observatory. Because one minute of time corresponds roughly to 15 minutes of arc, it is essential that the current *Ephemeris* be used.

A number of other methods, employing approximately the same principles, have been used from time to time, with some or much success. All, however, suffer from the fault that they can be applied only once a night, and not always at a convenient time. This time limitation becomes very serious in those parts of the world where clear night skies during the field season are not common, so that the amount of night work required to find true north becomes excessive and very costly.

ATEMPORAL METHODS.

Desirable, for the use of field geologists, is some method of determining true north which can be applied in a few minutes, whenever Polaris and some other identified star are visible, and which gives, with a minimum of computation, a very close approximation of true north.

This can be done, at present, by use of standard navigational equipment and methods, most of which are not known to the average competent instru-

[1] Lahee, F. H.: Field Geology, pp. 493–495, New York, 1941.

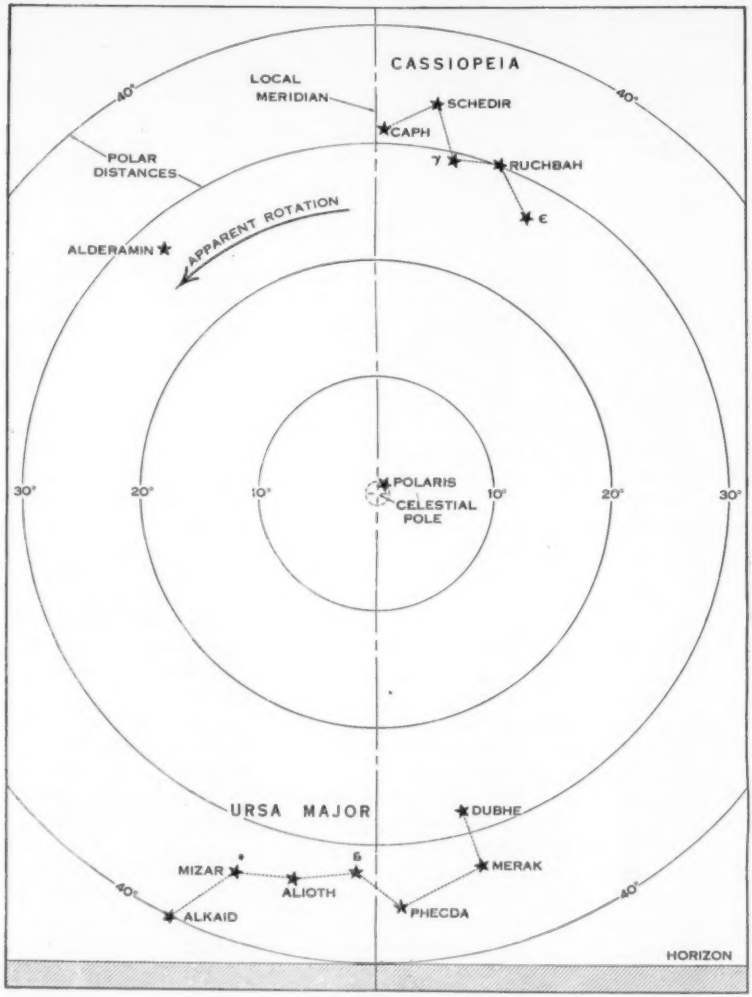

FIG. 1. Polar chart showing positions of principal navigational stars, relative to celestial pole and local horizon, at 00 hours Local Sidereal Time, and Latitude 40° north. At other latitudes, other polar distance arcs will be tangent to the local horizon. At other times, the relations of the stars to the local meridian will be changed, as the entire configuration, as seen by a terrestrial observer, revolves counterclockwise about the north celestial pole once each sidereal day.

ment man, who is already expected to have a wide variety of specialized skills.

The atemporal method of determining true north uses no principles not known two centuries ago. Perhaps it has been overlooked, in practical use, because of its theoretical simplicity. Quite certainly, it involves no instrument or computation not well within the range of experience of the average field geologist. By its use, a good "field" determination can be made in less than fifteen minutes: and a "six figure" determination is one hour or less, provided the instruments permit such accuracy.

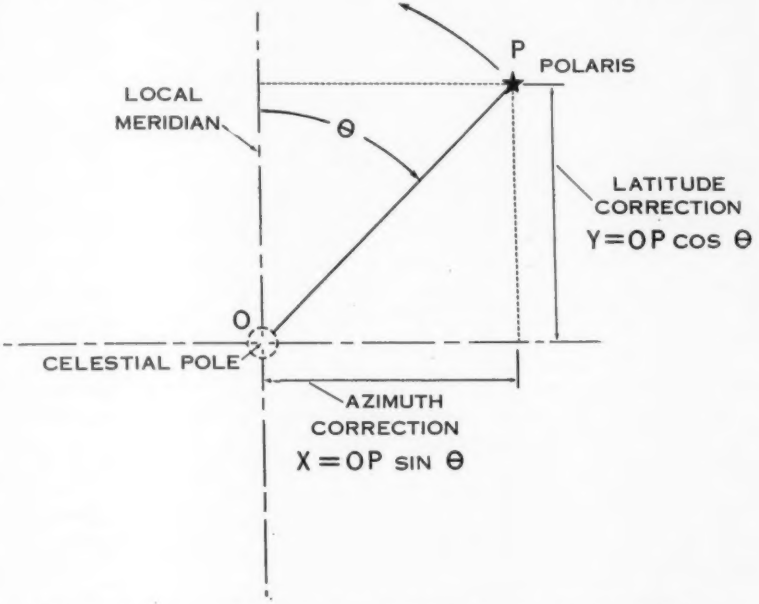

FIG. 2. Relation of Polaris to the celestial north pole, showing derivation of azimuth and altitude corrections. Θ is the position angle of Polaris at the instant considered.

Basic Theory.—1. If the position angle of Polaris, relative to the north celestial pole, is known, the azimuth and altitude corrections necessary for determination of true north and true latitude from that position of Polaris can be found by simple trigonometry. This is shown in Fig. 2. Where Θ is the position angle of Polaris at the instant considered, the azimuth correction is OP sin Θ, and the altitude correction is OP cos Θ.

2. The celestial north pole, Polaris, and any other star form a triangle, with two sides and the included angle known (sides are the polar distances of the respective stars; the included angle is the difference between their

right ascensions or their Greenwich hour angles) and, for most purposes, of constant dimensions. From these data, all other parts of the triangle can be computed, or, preferably, precomputed.

3. In consequence, the position angle of Polaris (Θ), relative to the celestial north pole and the local meridian, can be found by adding a constant angle to the position angle, relative to the local meridian, of a line connecting Polaris and any other identified star.

4. The position angle, relative to Polaris and to some terrestrial parameter, such as the horizon or a line perpendicular to it, of any star, can be found in the field by use of one or more standard and obvious observational procedures, followed by a simple computation.

TYPICAL APPLICATIONS.

Introduction.—The general theory here outlined may be applied, at least theoretically, to Polaris and any other identified star. Practical field usage, however, requires that the star chosen as the "guide star" be one which can be identified by the average instrument man, and one for which position constants are easily available. This immediately limits the choice of guide stars to those of numerically low magnitude which are listed in the American Ephemeris or equivalent tables, and which are visible from the field location. For sites in the north temperate zone, this limits the choice of guide stars to sixteen of magnitudes numerically smaller than 3, and with declinations exceeding about 50°. Of these, six, Dubhe, Merak, Phecda, Alioth, Mizar, and Alkaid, are in the constellation Ursa Major ("The Big Dipper," "The Plough"); four, Caph, Schedir, γ, and Ruchbah, are in the constellation Cassiopeia; and the remaining six are scattered through four other constellations. Positions of eleven of these stars are shown to scale in Fig. 1.

Under most conditions, when Mizar, a visual binary (double star) at "the bend of the handle" in Ursa Major (Fig. 1), is visible, it is the most convenient guide star. Ruchbah, in Cassiopeia, is a convenient guide at other times.

Relations of these two guide stars to Polaris, the celestial north pole, and the horizon, are shown, not to scale, in Fig. 3, with the dimensional designations necessary for the computations which follow.

Fundamental Relations—Mizar

In Fig. 3, left portion:

Θ = position angle of Polaris = $\Phi + \alpha$

α is an astronomical constant

$$\Phi = \arccos \frac{HP - HM}{MP} = \arcsin \frac{MN}{MP}$$

HP, HM, and MN are determined from field observations.
Only one function of Φ need be determined.

MP is an astronomical constant.

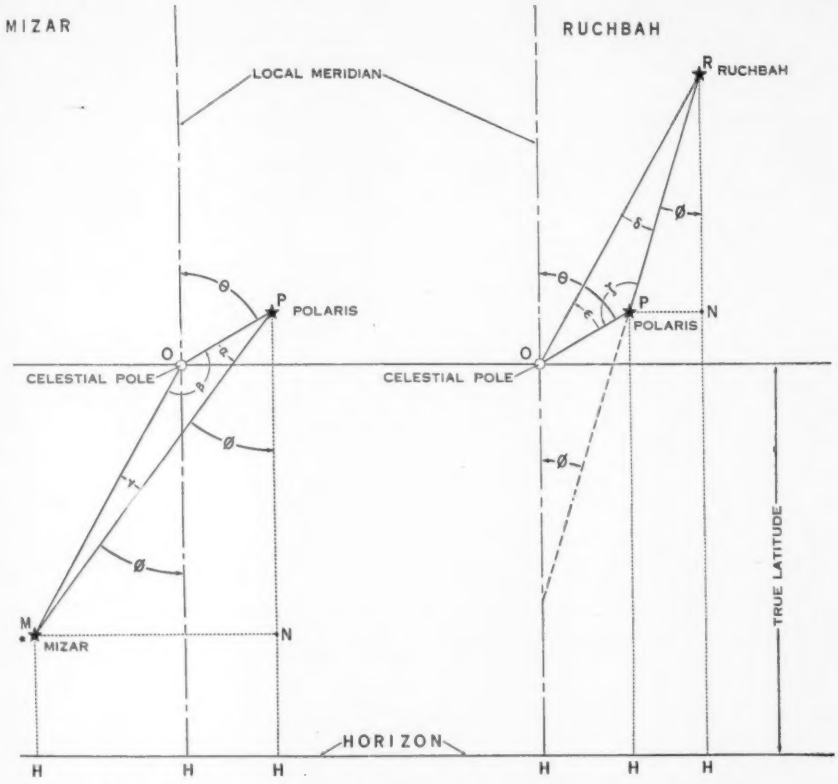

FIG. 3. Fundamental relations of stars, celestial pole, and horizon for determination of position angle of Polaris. This figure is not to scale.

Fundamental Relations—Ruchbah

In Fig. 3, right portion:

Θ = position angle of Polaris = $\Phi + \delta + \epsilon$
δ and ϵ are astronomical constants

$$\Phi = \text{arc cos}\,\frac{HR - HP}{RP} = \text{arc sin}\,\frac{NP}{RP}$$

HP, HR, and NP are determined from field observations.
Only one function of Φ need be determined.
RP is an astronomical constant.

Necessary Astronomical Data.—Determination of the position angle of Polaris from field observations requires the solution of the astronomical triangle OPM in the case of Mizar, and of OPR in the case of Ruchbah.

Specific needs are the lengths of the sides MP and RP, and the magnitudes of the angles α, δ and ϵ. These values are here referred to as astronomical constants, because they are figures which may be determined in advance to any accuracy desired, up to 99.99999 + percent, and not because they are invariants, although, for most practical purposes, assumption that they are invariants is justifiable.

None of these desired figures are given directly in any ordinarily-available astronomical table, but the declinations and right ascensions of the stars concerned are, and from these data the astronomical triangles can be solved for the needed constants. In addition, these computations can be made far in advance of need, at a convenient time and location, so that computation in the field is reduced to a minimum.

Available Astronomical Data.—From the American Ephemeris and Nautical Almanac, or any one of a number of equivalent tables, the following data, for the year 1948, can be determined:

Star	Right Ascension	Declination
Polaris	01h-47m-30.80s	89° 01′ 08″
Mizar	13h-21m-50.09s	55° 11′ 47.1″
Ruchbah	01h-22m-23.63s	59° 57′ 56.9″

These are the mean positions for the year, taken at the middle of the year. If higher accuracy is desired, the same data can be obtained from the same source for any desired date and time. In general, use of the mean position for the year will be accurate within less than 0° 05′, if the accuracies of the other measurements are compatible.

Reduction of Astronomical Data.—From the foregoing data, the lengths of the radius vectors of the respective stars are found by subtracting their declinations from 90°, the length of the radius vector being the polar distance of the star. The declination is the angular distance of the star from the celestial equator, as measured along a celestial meridian. For convenience in later computations, these are expressed in degrees and decimal fractions thereof.

The angles included between the radius vectors are found by simple subtraction of the respective right ascensions. For convenience, they are first subtracted, and the resultant angles converted from time units (hours, minutes, and seconds) to arc units (degrees, minutes, and seconds) by either multiplication (1 hour of time = 15 degrees of arc) or use of standard tables.[2] Where the field instruments read in units other than degrees and decimals thereof, field computations may be simplified by use of similar tables.[3]

Pertinent Reduced Values.—The following values, obtained from astronomical tables, by simple conversion and reduction, are pertinent to this computation.

For Mizar:

$$OP = 0.981111°$$
$$OM = 34.803305°$$
$$\beta = 173° 34′ 49.35″$$

[2] Smithsonian Meteorological Tables, Table 20, or equivalent.
[3] Smithsonian Meteorological Tables, Table 24, or equivalent.

For Ruchbah:

$$\begin{aligned} OP &= 0.981111° \\ OR &= 30.033917° \\ \epsilon &= 06° 16' 47.55'' \end{aligned}$$

Computation of Needed Values.—Needed astronomical values are the side MP and the angle α for Mizar, or the side RP and the angle δ for Ruchbah. In both cases, the reduced data from astronomical tables gives two sides of the triangle to be solved, and the angle included between them. In consequence, the third side can be found from the formula:

$$MP = \sqrt{\overline{OP}^2 + \overline{OM}^2 - 2\,\overline{OP}\,\overline{OM}\cos\beta}$$

(law of cosines, here stated for triangle OPM)

From which, by substitution and performance of the indicated operations, MP = 35.7409°, or 35° 44′ 23.73″. The decimal form is usually the most convenient for field computation.

The needed angle, α can be found from:

$$\alpha = \text{arc sin}\,\frac{OM \sin\beta}{MP}$$

(law of sines, here stated for triangle OPM)

From which, by substitution, $\alpha = 6° 35' 38''$, or 6° 35.63′, or 6.5938°.

In an identical manner, the needed constants for Ruchbah are found as: RP = 29.0610°, or 29° 03′ 39.72″, and $\delta = 0° 12' 16.62''$, or 0° 12.28″, or .2064°. For practical use, this must be added to the value of ϵ already found, so that $\delta + \epsilon = 06° 29' 04.17''$.

Working Formulas.—With the needed astronomical constants determined, the actual field procedure for determining a latitude or an azimuth from the position of Polaris is quite simple. The observations are:

Using a bubble sextant, theodolite, or transit, determine HP and either HM or HR (Fig. 3).

OR

Using an elevated alidade, sighting compass, theodolite, or transit, determine either MN or PN.

AND

Record position of Polaris at this same time.

The angle Φ is evaluated from:

$$\frac{HP - HM}{35.7409} \quad \text{or} \quad \frac{HR - HP}{29.0610} = \cos\Phi$$

$$\frac{MN}{35.7409} \quad \text{or} \quad \frac{PN}{29.0610} = \sin\Phi$$

Substitution in any one of these formulas gives the desired function of the needed angle. Formula to be used is determined by the instruments available and the star that is used as a guide.

Determination of the quadrant of Φ can be made from an obvious, but by no means simple, set of mathematical rules, which will not be detailed here, or from the following:

(a) The quadrant of Φ is the same as the quadrant of Polaris with respect to Mizar as a center.

(b) The quadrant of Φ is the same as the quadrant of Ruchbah with respect to Polaris as a center.

To determine θ,, add to Φ 6° 35.63′ (α) if Mizar is used as a guide; and 6° 29.07′ ($\delta + \epsilon$) if Ruchbah is used.

The azimuth correction is: $0.98111^\circ \times \sin \theta$
The latitude correction is: $0.98111^\circ \times \cos \theta$

Both corrections, which are angles, are turned from the position of Polaris at the time of the initial observation toward Mizar, and away from Ruchbah. Numerical values here given are mean values for 1948, and should be checked, and recomputed if necessary, for other years.

Alternative Methods.—A considerable number of workable alternatives to the methods outlined above are possible, and most of them should be obvious. Most of these are based on the relations:

$$\Phi = \text{arc tan} \frac{MN}{HP - HM} = \text{arc tan} \frac{PN}{HR - HP}$$

A rough check on the computations is furnished by the approximation:

$$\sin \text{ or } \cos (\Phi + 6.5^\circ) = \text{azimuth or altitude correction.}$$

SUMMARY AND CONCLUSIONS.

The methods of determining true north or true latitude here outlined appear practical and workable under a wide variety of field conditions, but are particularly suited for work of medium accuracy under conditions where time is at a premium, or where visibility conditions permit only one or two "sights" a week.

Attainable accuracy, if annual mean values for astronomical constants are used, is about 5 minutes of arc, provided such accuracy is permitted by the instruments used. With suitable instruments, and astronomical data computed for the day and hour, accuracies of one second of arc may be attained in practice; and even greater accuracies are theoretically possible, although seldom attained because of random minor shiftings of the earth's axis.

INDIANA UNIVERSITY,
BLOOMINGTON, IND.,
Mar. 25, 1948.

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DISCUSSION AND COMMUNICATIONS

Sir: This JOURNAL (vol. 43, p. 133, 1948) contains a paper by my former student Mahmoud Sayed Amin on some chromites from Egypt. Having worked for many years on the geology of the Barramia and Um Salatit area I would like to make the following comments. The paper ascribes the origin of the lenticular chromite bodies, which form the exploited ore of the area, to an early crystallization and segregation of the chromites from a peridotite magma. "Then the crystallized bodies were carried by the ultramafic magma as solid inclusions" (Introduction p. 133). In another place (p. 151) the chromites are stated (following Thayer) to be carried by "the silicate fluid which was intruded and crystallized at a later stage." The main evidence given (pp. 150 and 152) is that the composition of the chromites and the so-called ultramafics in which the lenses are found are not "complementary" with respect to their MgO and FeO content. The writer is of the opinion that the evidence given is contradictory and may not be correct.

An inspection of the equivalent mg values of the chromites and associated rocks (p. 148) shows that there is an actual increase of the mg values of the serpentines and talc-carbonate (Amin's ultramafics) ranging from 95.5–97.8 when compared with the values of the enclosed chromites, ranging from 84.7–93.8. The difference could not have been more pronounced as is the case in some of the Bushveld occurrences,[1] because the Egyptian chromites are very poor in FeO from the start, the molecular ratio of FeO : MgO in one chromite is 26 : 336, with mg values ranging from 84.7–93.8 as compared with 27.1–41.6 for the Bushveld chromites. The Egyptian chromites and their associated ultra-basics are thus "complementary" as in the case of certain of the Bushveld rocks. Thus the evidence given would not seem to support a late intrusion of the solid chromite lenses, and they could have been formed *in situ* from the same magma, now serpentine and talc-carbonate, in which they are present. On p. 148 it is stated that the composition of the chromites indicates that they were formed in forsteritic rocks and associated with feldspar-free peridotite, low in alumina and iron oxide (olivine-enstatite rock). The actual serpentine surrounding lens No. 1 is described as having been originally an olivine-pyroxene peridotite (p. 141) and that surrounding deposit No. 2 as dunite containing a small amount of pyroxene (p. 143).

The sequence of crystallization of the chromite and silicate minerals and the ratios of the different constituents in the minerals and in a specific ultra-basic magma from which they are crystallizing, are complicated problems.

No attempt was made to clarify the stage at which, and means by which, the actual separation of the solid chromites (from their original magma into the silicate rocks in which they are now present) took place. Again, the ef-

[1] Van der Walt, C. F. J., Geol. Soc. South Africa Trans., vol. 44, pp. 79–112, 1941.

fect of the formation of the early-formed iron-poor and magnesia-rich chromite on the nature of the residual magma is not considered. The nature of the magma in which the solid inclusions were carried and its relation to the original magma from which the chromites of the lenticular bodies were formed is not mentioned. This causes an ambiguity when the carrying up of the chromites is described (pp. 133, 151–152). Much more work on the chromites is needed before any conclusion can be drawn. Analysis of the disseminated ore, described as having crystallized from the ultra-basics surrounding the lenticular bodies, and of the veinlets, is now being undertaken.

Again, only four analyses of the chromites and three of the ultra-basics are given and the so-called ultramafics analyzed were not only altered to serpentines in two cases (changing their magmatic composition) but are affected by a carbonation process (in the third case) which metasomatically replaced the serpentines as well as the country rocks in which they were intruded into talc-carbonate rocks all over the area; to take the mg values of these talc-carbonate rocks as representing the original magma and to establish a comparison is strange. Chemical analyses of rocks from the area under my disposal show the fallacy of such a comparison. Again two of the analyses of chromites, out of a total of four, used by Amin in his evidence are described by him (pp. 151–152) as being of a secondary origin and are derived from pre-existing chromites by magmatic and hydrothermal action. The altered chromites (A′ and B) are described as showing great decrease of magnesia and small increase of ferrous iron (p. 150), as compared with the unaltered chromites (A and C). Again the gangue of chromite B is calculated as talc, whereas the interspaces are described as filled with chlorite, talc and magnesite (p. 144). The ratio of MgO : FeO in the chlorite is taken as that of the chromitite and the ratio of SiO_2 : MgO in the calculated talc is 1 : 1 whereas in the formula it is 4 : 3 (p. 146). Also in Table II the MgO of the gangue of C should be 146 instead of 99, Fe_2O_3 of the calculated chromite should be 94 instead of 97 and of MgO 99 instead of 106. More remarks could be given but sufficient has been said to show the incorrectness of some of the conclusions.

This brings me to the alteration of the chromites described in the paper. The released alumina from the outer margins of deposit No. 1 or from the lenses of deposit No. 3, during alteration, is stated to have changed "the serpentine in the interspaces to chlorite" (p. 141). In another place (p. 151) it is stated that the "removed alumina from the altered chromite is assumed to be fixed in the chlorite instead of serpentine in the interspaces of the chromite crystals." It is assumed that Amin means in this last quotation the serpentine in which the lenses are found and not the serpentine, now altered to chlorite, of the lenses themselves. It is strange that Amin visualized the released alumina to have altered the serpentine between the interlocked crystals of chromite of the central part of the lens (deposit No. 1) into chlorite, instead of replacing the green serpentine sheath which surrounds the chromite lens (pp. 136 and 141) and is *adjacent* to its outer altered part (one cm thick), especially as the line of contact is a very easy channel for the migration of material. Again the actual replacement of serpentine by chlorite was not seen,

as the interspaces of the central part of the lens and of the margins are described as being formed of chlorite only (pp. 137 and 140); the supposed evidence of replacement is unfortunately obscured. Likewise no evidence of replacement of talc by chlorite due to the same cause (pp. 144, 151) is given.

Again, magnesia is said (p. 141) to have been released during the alteration and that it formed "magnesite that appears in the marginal zone either as grains in the interspaces (Fig. 14) or as veinlets cutting the ore (Fig. 15)." In another place (p. 151) the magnesite is said to be "relatively insufficient to account for the removed magnesia," in spite of the fact that altered chromites of deposit No. 3 are found in talc-carbonate rocks. It is unfortunate that Amin did not give any evidence that the magnesite grains and veinlets are formed by the released magnesia from the altered chromites (leaving aside the question of the quantities released) and also overlooked or ignored the presence of carbonate veins more than a meter thick and some hundreds of meters long, and other smaller veins and lenses and disseminated grains, which are distributed all over the area in the different lithological varieties: hornblendic rocks, graywackes, mudstones, etc. These carbonates are caused by the carbonation process mentioned above, which formed the talc-carbonate rocks of the area such as that in which the described altered lenses (deposit No. 3) are found. The carbonate grains and veinlets described by Amin could very possibly be due to the carbonates formed during the alteration of serpentine into talc through the action of CO_2 which affected the whole area (contrast Figs. 21 and 25; also the magnesite of Fig. 25 is indistinguishable from carbonates of the so-called matrix).

A few incorrect statements are found throughout the paper. For instance, the peridotite magma is described (p. 152) as being low in iron and in magnesium. It is low in iron and aluminum. The variation of the mg values (p. 150) in the Egyptian chromites are given as 84–92 instead of 84.7–93.8 and of the Bushveld chromites as 30–40 instead of 27.1–41.6 For example, the lens of deposit No. 1 is described as being situated 1 km east of Barramia well (p. 136); its location is west of the well. Again the two diameters of the same lens given in Fig. 3, p. 136, do not correspond with the diameters given in the text. Such mistakes may be due to the hurried nature of the work and it is to be regretted that such beautifully reproduced figures are wasted on material that is not correct in all details. At present the chromites and associated rocks and the detailed geology of the area are still under investigation.

N. M. Shukri.

Geology Department,
Faculty of Science,
Abbassia, Cairo,
May 24, 1948.

REVIEWS

Eruptive Rocks, Their Genesis, Composition, Classification, and Their Relation to Ore-Deposits, 3rd. Ed. By S. JAMES SHAND. Pp. 488; figs. 51; pls. 4. John Wiley and Sons, New York, 1947 (1948). Price, $7.50.

This book by one of our outstanding petrologists immediately won a name for itself in the first two editions among petrologists and geologists. In the new edition one can see a number of changes. The chapter on "Eruptive Ore Deposits," omitted from the last edition, is reinstated in revised form and three entirely new chapters have been added. They are, Chapter X, Late-magmatic and Post-magmatic Reactions; Chapter XI, The Genesis of Pegmatite; and Chapter XII, Eruptive Rocks and Ore Deposits. These three chapters will be welcome particularly by economic geologists. Much new matter has been introduced throughout the other chapters and several new illustrations have been added and considerable re-arrangement of topic matter has taken place.

The new contents by chapters are now as follows: Eruptive or Igneous Rocks; The Fixed Constituents of Eruptive Rocks; The Fugitive Constituents of the Magma; Temperature and Pressure in the Magma; The Magma and its Walls; The Freezing of Silicate Melts; The Freezing of Rock Magma; Compatible and Incompatible Phases; Eruptive Rock Complexes; Late-magmatic and Post-Magmatic Reactions; The Genesis of Pegmatite; Eruptive Rocks and Ore Deposits; The Classification of Eruptive Rocks; A System of Petrography; Oversaturated Rocks—Occurrence and Genesis; The Saturated Rocks—Occurrence and Genesis; Undersaturated (Non-feldspathoidal) Rocks—Occurrence and Genesis; Undersaturated (Felspathoidal) Rocks—Occurrence and Genesis; Meteorites and the Pre-geologic History of the Earth; The Oversaturated Rocks; The Saturated (and Slightly Oversaturated) Rocks; Undersaturated (Non-feldspathoidal) Rocks; Undersaturated (Feldspathoidal) Rocks.

The general concept contained in a paper by the author published in the American Journal of Science in 1944 in regard to petrologic procedures and problems is generally followed throughout this book and the writer has followed still further his own procedures, terminology and nomenclature. The book will be of interest to all advanced students of petrology.

General Chemistry. By LINUS PAULING. Pp. 595; figs. 117. W. H. Freeman and Co., San Francisco, Calif., 1947 (1948). Price, $4.25.

This book by America's outstanding chemist is styled "An Introduction to Descriptive Chemistry and Modern Chemical Theory." It should serve not only as an excellent elementary textbook but as a book for every scientist who wishes to keep up with the advance in knowledge of the atom, the molecule, the periodic system, the chemical bond. It is so well and so clearly written that it should interest those who are not scientists and wish to know something of chemistry.

The 33 chapters cover the following subjects: Nature and Properties of Matter; Atoms, Molecules, and Crystals; Elements, Elementary Substances, and Compounds; The Periodic Law; Weight Relations in Chemical Reactions; Ions,

Ionic Valence, and Electrolysis; Covalence and Electronic Structure; Oxidation-Reduction Reactions; Chromium and Manganese, and Related Metals; Halogens; Laws of Electrolysis; Properties of Gases and Solutions; The Rate of Chemical Reactions; Chemical Equilibrium; Acids and Bases; Solubility Product and Precipitation; Complex Ions; various metals and other minerals; Organic Chemistry; The Chemistry of Silicon; Thermochemistry; Oxidation-Reduction Equilibria; Radiochemistry.

The many clear and interesting illustrations clarify a vivid text and help to make the complex science seem clear to the initiated. Nevertheless it is solid and substantial chemistry throughout. This book will be very valuable to hard rock geologists.

Mineral Resources of the United States. By the STAFFS OF BUREAU OF MINES AND GEOLOGICAL SURVEY. Pp. 212; figs. 37; charts 29. Public Affairs Press, 2153 Florida Ave., Washington 8, D. C., 1948. Price, $5.00.

This attractively printed and illustrated book is a reprinting of pages 175–310 of the Government publication entitled "Hearings before a Subcommittee of the Committee on Public Lands, U. S. Senate, First Session on Investigation of the Factors Affecting Minerals." Two changes are noted however: The new book contains a foreword by the Secretary of the Interior and omits from beneath the section headings the names of the writers of those sections. Over 100 names appear as authors.

This is the most authoritative book on the mineral resources of the United States yet published. Part I consists of a summary, in which the mineral position is shown by a group of excellent charts, and deals with the method of the report, deficiencies of data and a history of the industry. Part II covers the search for new supplies, and coal, oil, and treatment trends. Part III covers 39 metals and minerals separately giving specifications, sources, statistics, and reserves.

The Government points out that there is little likelihood of imminent exhaustion of many vital minerals such as coal, gas, iron ore, phosphate and others; that if the country can use known sub-marginal resources, we can become virtually self-sufficient in 21 minerals, partly dependent for 13 minerals and wholly dependent on foreign sources for 5 more.

The many tables, excellent charts, and maps are among the valuable features of the book.

The book appears at a very appropriate time now that there is so much discussion of our mineral resources, and the relation of the Marshall Plan to mineral supplies.

Chambers's Mineralogical Dictionary. Pp. 47; 40 colored plates. Chemical Publishing Co., Brooklyn, N. Y., 1948. Price, $4.75.

This handy dictionary is a new edition of the one first published in 1945. Over 1,400 mineralogical terms are included giving the chemical composition, crystal form, physical and chemical properties, occurrence and uses. The 40 colored plates show about 200 minerals; many of these plates are extremely good and will be helpful to enable the reader to recognize the minerals. Many others, however, might be almost anything and are not very diagnostic. Most of the plates depict only the crystal forms of the minerals; for example, one commonly sees cerussite, but rarely does one see the beautiful cerussite crystals pictured to illustrate the mineral.

This book will be a handy reference to all geologists, mineralogists and students of mineralogy. It should also prove extremely useful to mineral collectors throughout the country and to jewelers and chemists.

BOOKS RECEIVED.

ALAN T. BRODERICK.

U. S. Department of the Interior—Bureau of Mines.

Inf. Circ. 7428. Mining and Milling Methods and Costs at the Little Pittsburg Lead-zinc Mine, Shoshone County, Idaho. ROBERT J. HUNDHAUSEN. Pp. 21; figs. 6; tbls. 4. Washington, 1948.

Rept. Inv. 4121. Investigation of the Mount Eielson Zinc-lead Deposits, Mount McKinley National Park, Alaska. N. M. MUIR, B. I. THOMAS AND R. S. SANFORD. Pp. 13; figs. 5; tbls. 5. Washington, 1947. *Replacements of Paleozoic sediments along shears. Sample widths, Pb, Zn, Cu, Au, Ag assays given. Reserves not estimated.*

Rept. Inv. 4124. Blue Ledge Copper-zinc Mine, Siskiyou County, Calif. R. J. HUNDHAUSEN. Pp. 16; figs. 3; tbls. 4. Washington, 1947. *Replacements of schists along shears. 11,000 tons of .092 Au, 5.24 oz. Ag, 12.12% Cu produced up to 1930, mostly from development work. Beneficiation test results. Reserves not estimated.*

Rept. Inv. 4144. Akoz Mine, Mariposa County, Calif. FRANK J. WIEBELT. Pp. 6; figs. 3. Washington, 1947. *Lead-zinc replacements of schists. No ore found by 3 drill holes beneath shallow workings.*

Rept. Inv. 4188. Sidney Mine, Pine Creek Area, Shoshone County, Idaho. R. M. GAMMELL AND R. J. HUNDHAUSEN. Pp. 11; figs. 7. Washington, 1948. *Lead-zinc replacements along shears. New ore shoot found by trenching, drilling.*

Rept. Inv. 4189. Cle Elum Iron-nickel Deposits, Kittitas County, Wash. S. W. ZOLDOK. Pp. 8; figs. 4; tbls. 2. Washington, 1948. *Iron-nickel laterite from pre-Cenozoic weathering of serpentinized peridotite. Nickel controlled by faults. Sample assays given but no estimate of reserves made.*

Rept. Inv. 4209. Be Van Quartz Crystal Prospect, Lemhi County, Idaho. J. A. HERDLICK. Pp. 8; figs. 2. Washington, 1948. *Short quartz veins in granite augen gneiss. Small reserves, much unusable.*

Rept. Inv. 4216. Beryl Mountain, Sullivan County, N. H. S. B. LEVIN. Pp. 5; figs. 2. Washington, 1948. *Zoned pegmatite, beryl near quartz core.*

Geology and Artesian Water of the Alluvial Plain in Northwestern Mississippi. G. F. BROWN. Pp. 424; figs. 38; pls. 13; tbls. 30. Miss. Geol. Survey Bull. 65, University, 1947. *Flowing and near-flowing wells from 6 Eocene, Paleocene sands separated by clayey beds. Deeper waters softened by base exchange of aquifers. Origin of fluorine obscure.*

Local Floods in Ohio during 1947. WILLIAM P. CROSS. Pp. 66; tbls. 29; pls. 7; figs. 31. Ohio Water Resources Board Bull. 14. Columbus, 1948. *Rainfall amounts and intensities, peak stream discharges, damages caused by 7 cloudburst floods.*

Geology and Economic Minerals of Canada. By OFFICERS OF THE GEOLOGICAL SURVEY. Pp. 357; pls. 66; figs. 77. Canada Department of Mines and Resources, Economic Geology Series No. 1. Ottawa, 1947. *Summarizes geological investigations and mineral developments since 1842.*

Ontario Department of Mines—Annual Reports. Toronto, 1948.

Vol. 54, Pt. II. Mines of Ontario in 1944. List of Mines, Quarries, and Works Operating in 1944. Mining Accidents in 1944. Pp. 152.

Vol. 55, Pt. I. Statistical Review of the Mineral Industry of Ontario for 1945. List of Quarries and Works for Structural Materials and Clay Products, 1945. Mining Accidents in 1945. Pp. 101; tbls. 8.

Vol. 55, Pt. II. Mines of Ontario in 1945. List of Mines, Quarries, and Works Operating in 1945. Pp. 116.

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Estudos, Notas e Trabalhos. Pp. 116; numerous maps, figures and photos. Bureau of Mines and Geology of Portugal, Vol. II, Fasc. 3 and 4. Porto, 1946. *Six separate papers. One on the genesis of the pyrite masses of southern Spain (partly late magmatic, partly hydrothermal) Three on a magnetite deposit at Vila Cova do Marão. One on a serpentinized peridotite deposit near Cabeço de Vide. One on the analyses of mineral water from northern Portugal.*

Symposium of Information Relative to Uses of Aerial Photographs by Geologists. COMPILED BY H. T. U. SMITH; 14 PAPERS BY VARIOUS AUTHORS. Pp. 98; figs. 44, including photographs, charts, drawings and one reconnaissance map. In Photogrammetric Engineering, Vol. XIII, No. 4, Dec. 1947. Menasha, Wis. Price, $1.50. *Utilization of aerial photos in geologic mapping and research; photogrammetric techniques of value to geologists; use of aerial photos in college and university geology departments. Some excellent photographs and description of recent developments useful to geologists. Closer cooperation between geologists, other scientists, aerial photographers, and photogrammetrists would benefit all.*

SCIENTIFIC NOTES AND NEWS

LOUIS E. REBER, geologist with Phelps Dodge Corporation, is establishing his home in Morenci, Arizona, where his work is now centered. He was previously at the company's United Verde property.

R. C. GEBHARDT, geologist and engineer with the R. J. Longyear Company of Minneapolis, Minnesota, is making a business trip to Venezuela.

MASON W. RANKIN, geologist for the Northwest Geological Department of the American Mining and Smelting Company, has transferred his headquarters from Wallace, Idaho, to Helena, Montana.

FORBES S. ROBERTSON, of Rolla, Mo., who has been economic geologist for the Missouri Geological Survey, has joined the faculty of Montana School of Mines, teaching petrography and economic geology during the school year and working with Montana Bureau of Mines and Geology in the summer months.

GARNET C. MCCARTNEY has opened an office in Toronto as mining consultant. Dr. McCartney was previously employed by Transcontinental Resources, Ltd., and Central Porcupine Mines as geologist, and is retained by these companies in a consulting capacity.

CHARLES F. PARK, JR., Stanford professor of geology, will fly to Brazil in June for a three-months' project of mapping iron ore deposits and the general geological structure at Itabiri, north of Rio de Janeiro. The project, financed by the State Department, is being undertaken by the U. S. Geological Survey in cooperation with the Brazilian government. Dr. Park will return to the United States for the opening of the fall quarter at Stanford.

F. F. OSBORNE is now Professeur Titulaire de la Chaire de Pétrologie at the Faculté des Sciences of Laval University, Quebec.

ROBERT A. MACKAY has resigned from his position as Mining Geologist to the Geological Survey of Nigeria to take up the post of Senior Geologist in the Atomic Energy Branch of the Geological Survey of Great Britain. His new address is care of Lloyds Bank, Ltd., 6 Pall Mall, London, W.C.

OSCAR E. MEINZER, retired Chief of the Groundwater Division of the U. S. Geological Survey, died in Washington, June 15.